SAND2013-7991P

Exceptional service in the national interest

Sandia National Laboratories

Active control of complex far infrared plasmonic structures

This work is supported by the U.S. AFOSR under Contract No. FA9550-09-C-0168 and Physical Sciences Inc. (PSI) under Agreement No. FI011090528 and does not reflect the views of the U.S. AFOSR or PSI.

Gregory C. Dyer

Sandia National Laboratories

Monday, October 28th, 2013

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Outline

- Introduction
- Low dimensional far infrared plasmonic structures
  - Integrated 2D plasmonic devices
  - Strong coupling of tunable 2D plasmonic resonators
  - Generalized 2D plasmonic transmission line model
  - Active control of plasmonic crystal band structure
  - Electromagnetically induced transparency
- Conclusions & future directions

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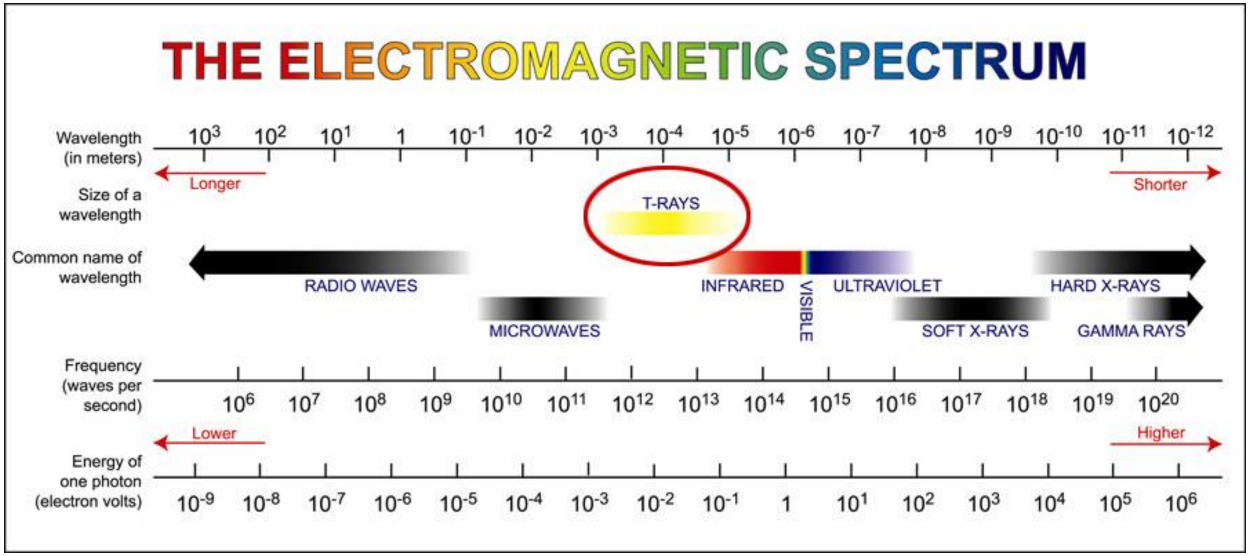
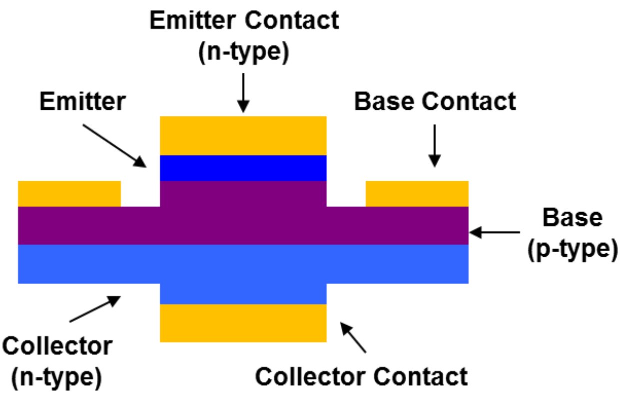
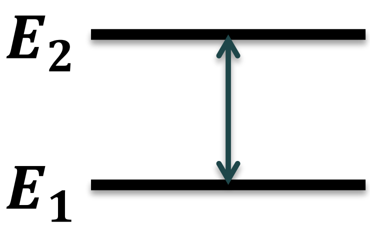
The ‘THz Gap’



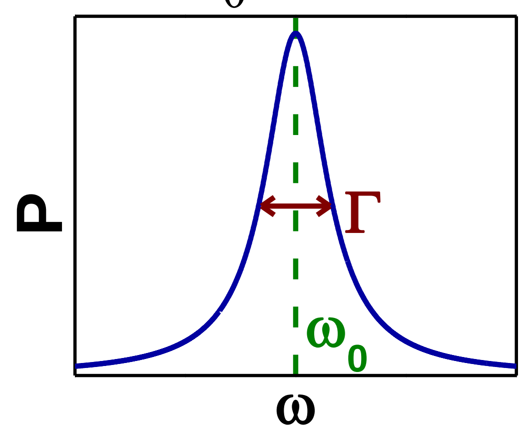
from *http://web.njit.edu/~barat/RBB_research.html*

Electronics	Photonics	Plasmonics
RC limited	*kT* limited	$Q = \omega_0/\Gamma$ limited



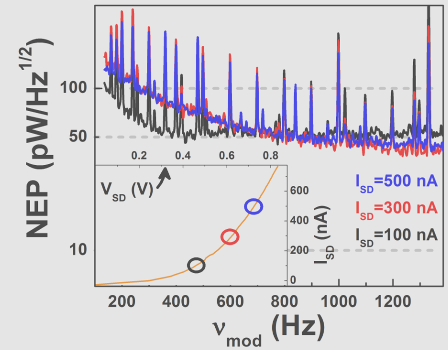


$$E_2 - E_1 = \hbar\omega \gg kT$$

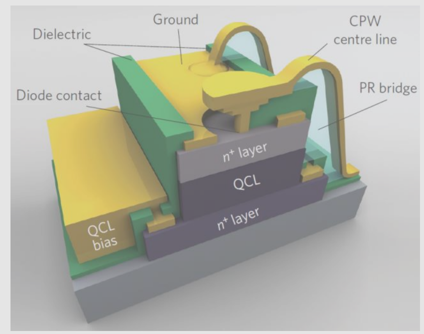


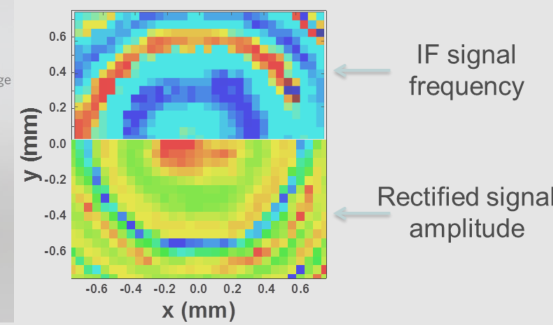
THz Electro-Optics at Sandia

- Far infrared plasmonic detectors

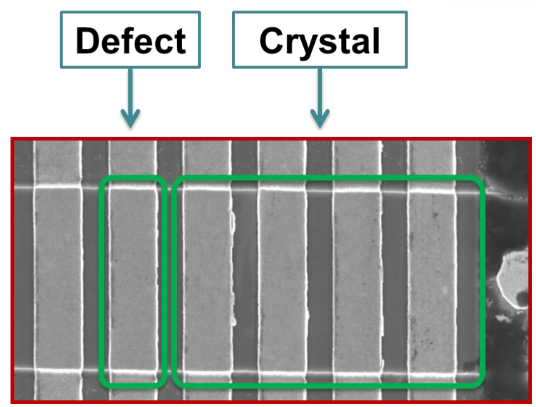


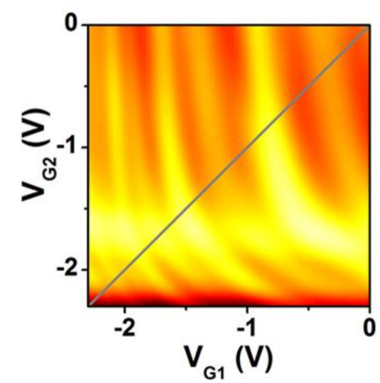
- Quantum cascade laser transceivers





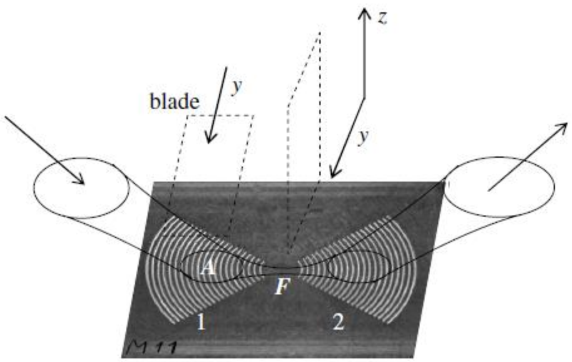
- Coherent low dimensional plasmonic phenomena

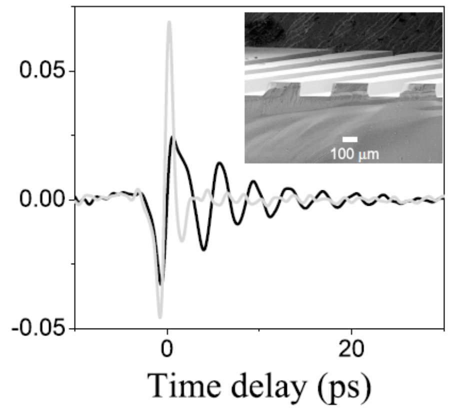




Far Infrared Plasmonics

Metal & Semiconductor Gratings

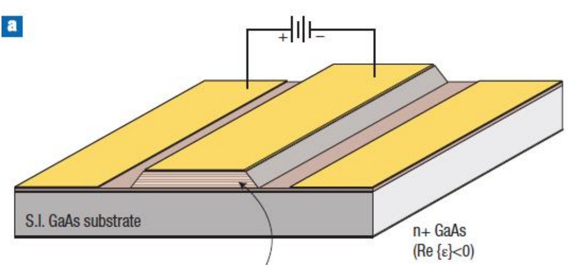


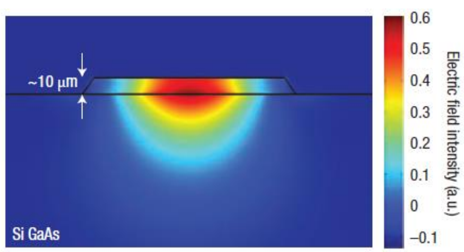


G. Gaborit *et al.*, *APL* **94**, 231108 (2009)

J. G. Rivas *et al.*, *PRL* **93**, 256804 (2004)

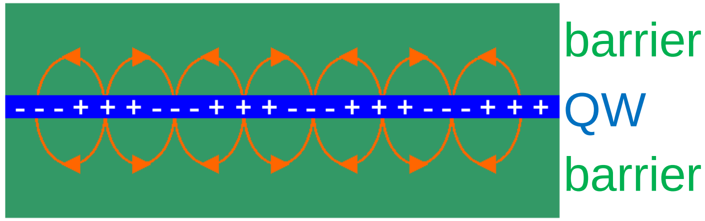
Quantum Cascade Laser Cavities



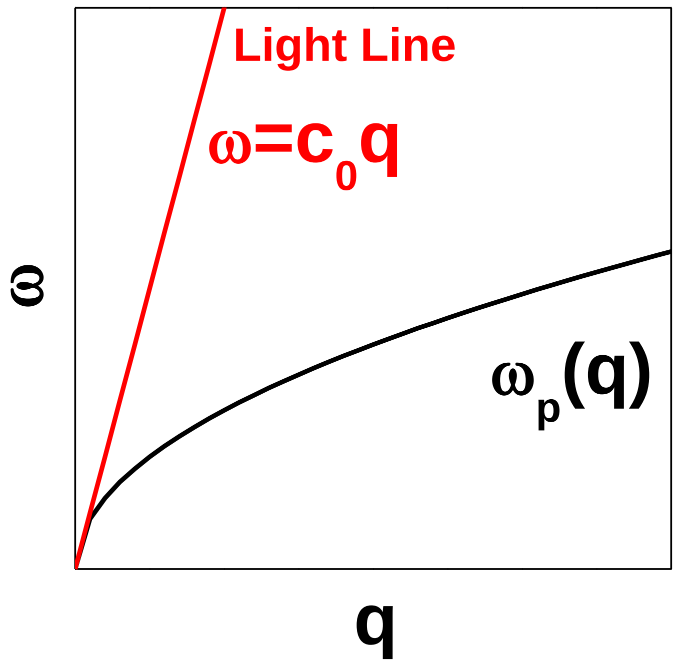


B. S. Williams, *Nat. Photonics* **1**, 517 (2007)

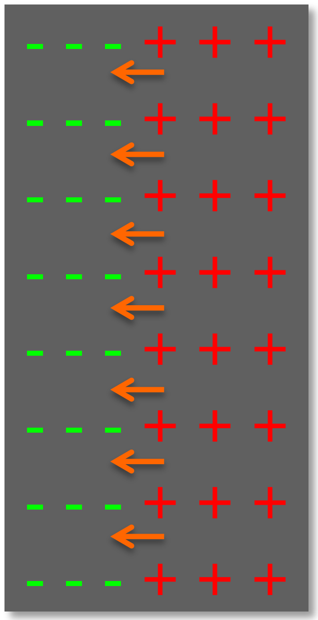
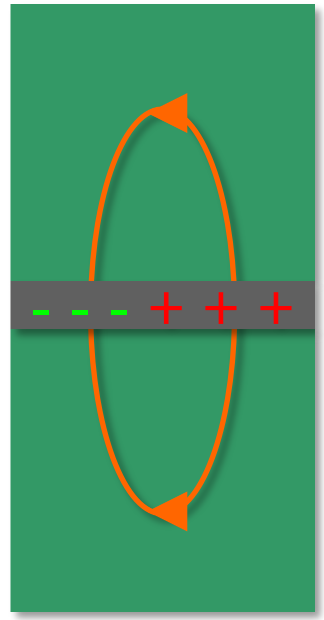
Semiconductor 2DEGs

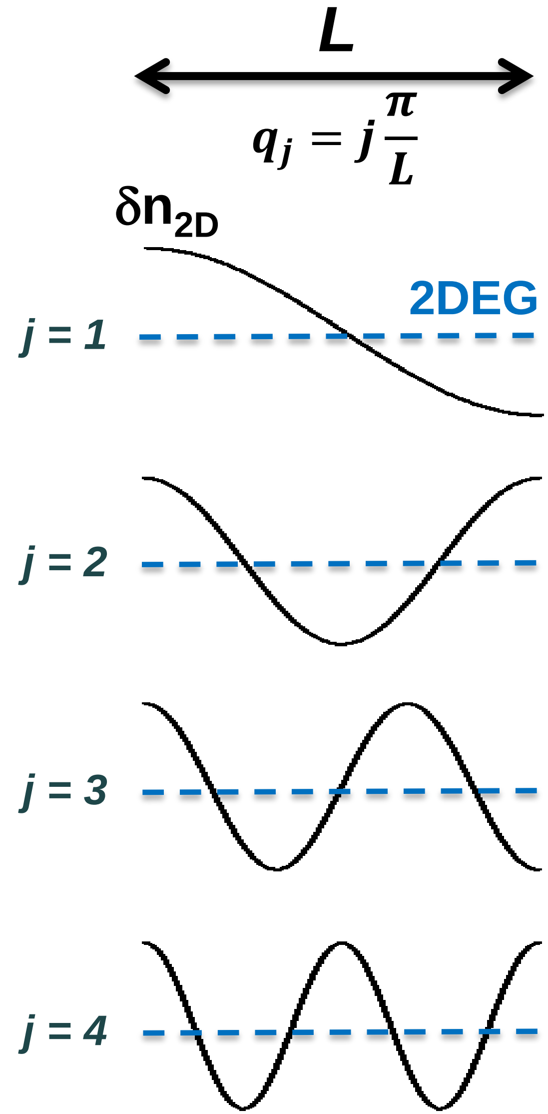


$$\omega_p = \sqrt{n_{2D} e^2 q / 2\epsilon m^*}$$



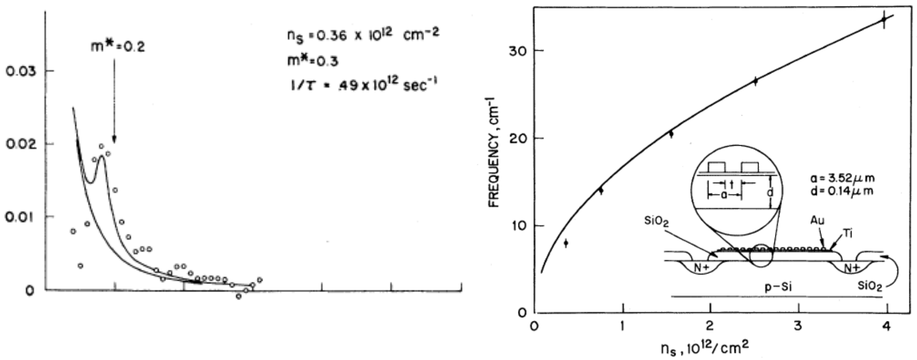
Bulk to 2D plasmons

	Bulk	*2D*
Geometry		
Units	$n_{3D}[m^{-3}]$	$n_{2D}[m^{-2}] \times q[m^{-1}]$
Plasma Frequency	$\omega_p{}^{3D} = \sqrt{\frac{n_{3D}e^2}{\epsilon m^*}}$	$\omega_p{}^{2D} = \sqrt{\frac{n_{2D}e^2 q}{2\epsilon m^*}}$



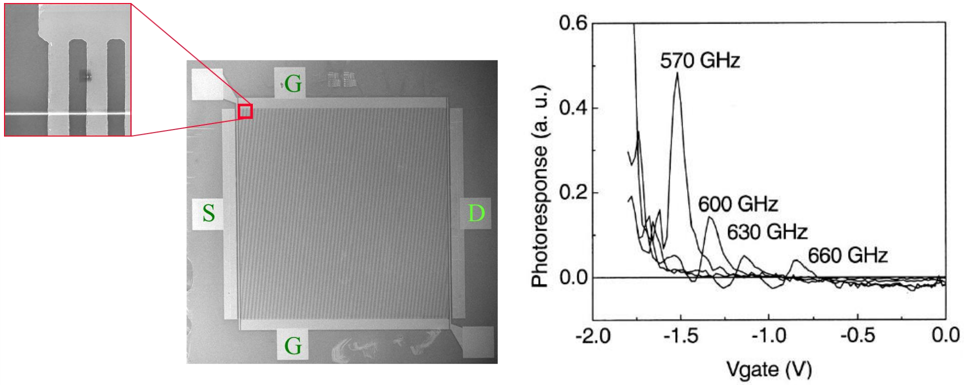
FIR 2D Plasmonic Systems

Grating Gated Si MOSFETs



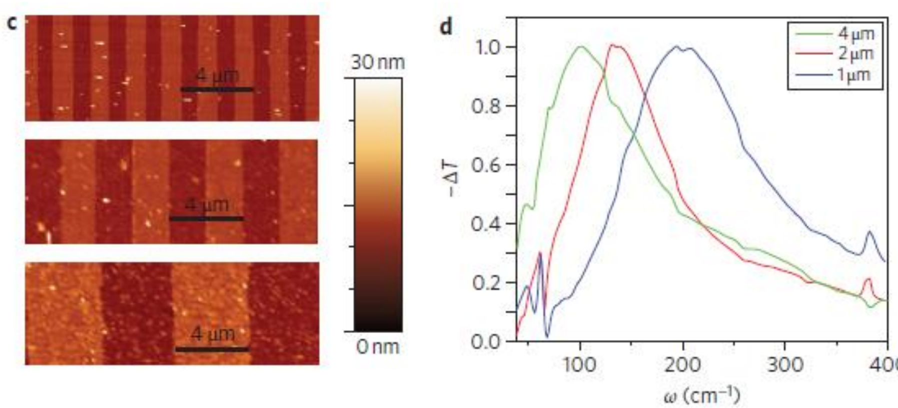
S.J. Allen *et al.*, *PRL* **38**, 980 (1977)

Grating Gated GaAs/AlGaAs HEMTs



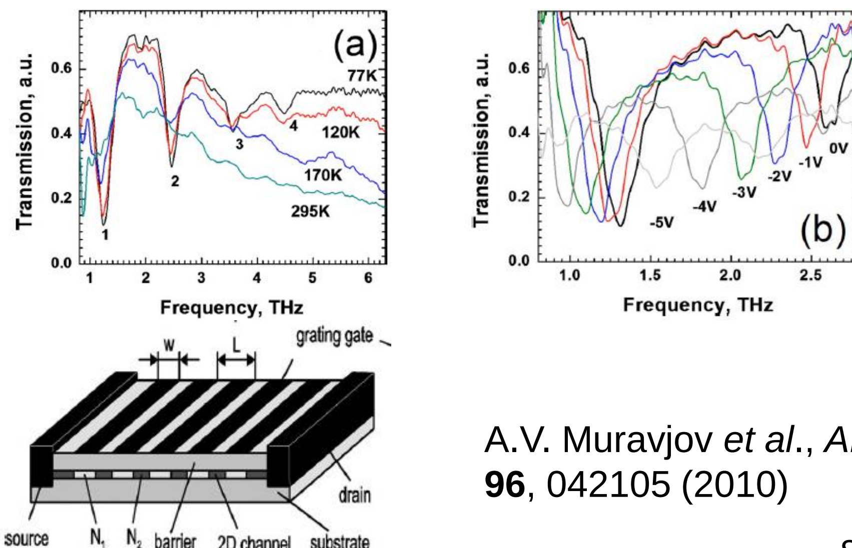
X.G. Peralta *et al., APL* **81**, 1627 (2002)

Graphene Gratings



L. Ju *et al.*, *Nat. Nano.* **6**, 630 (2011)

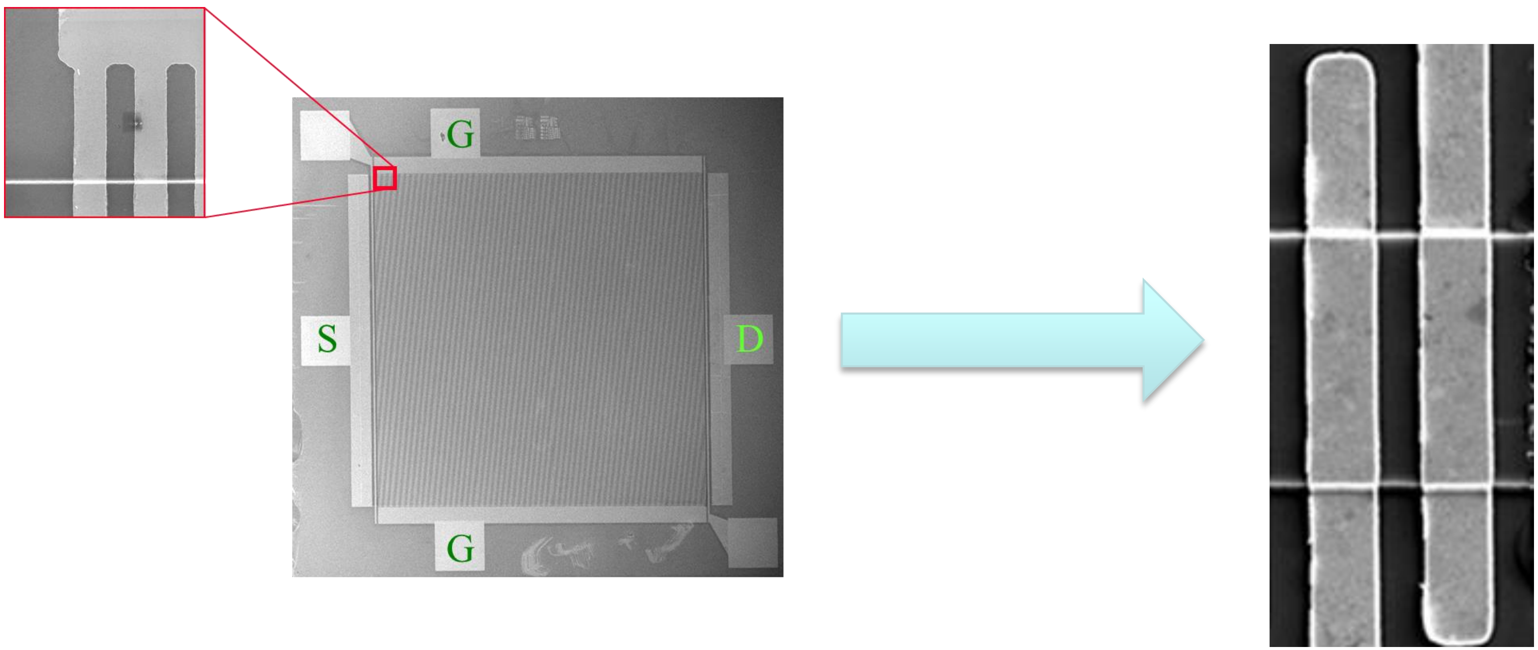
Grating Gated GaN/AlGaN HEMTs



A.V. Muravjov *et al.*, *APL* **96**, 042105 (2010)

From Plasmonic Arrays to Elements

- Plasmon-plasmon coupling?
- Plasmonic dispersion in coupled structures?
- Plasmon damping & coherence length?



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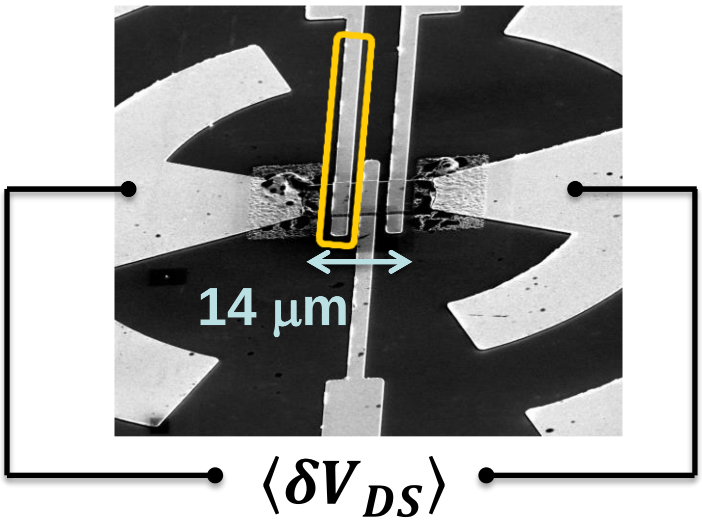
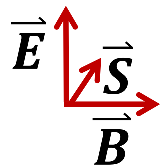
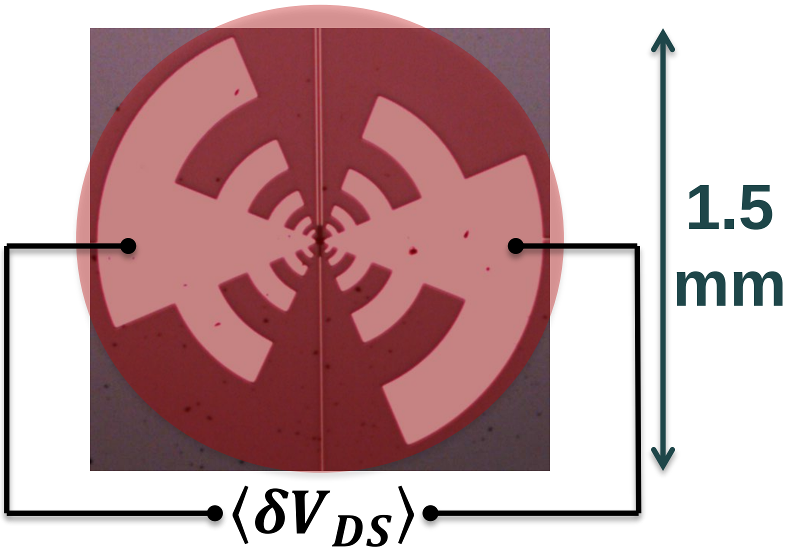
Integrated 2D Plasmonic Devices

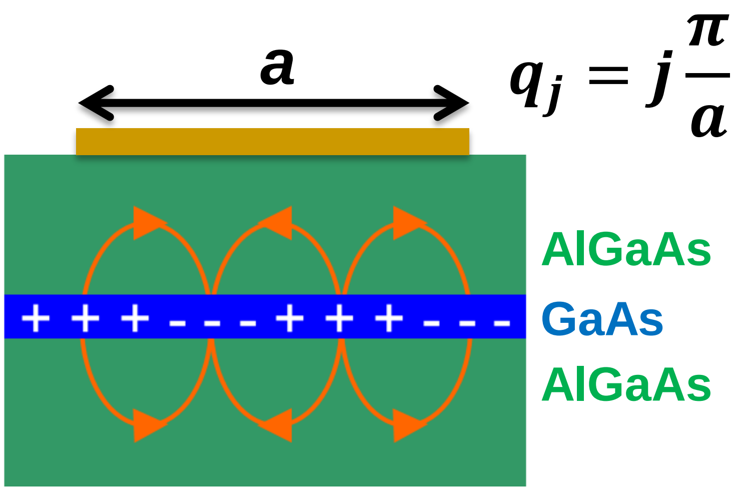




0.1 - 0.5 THz



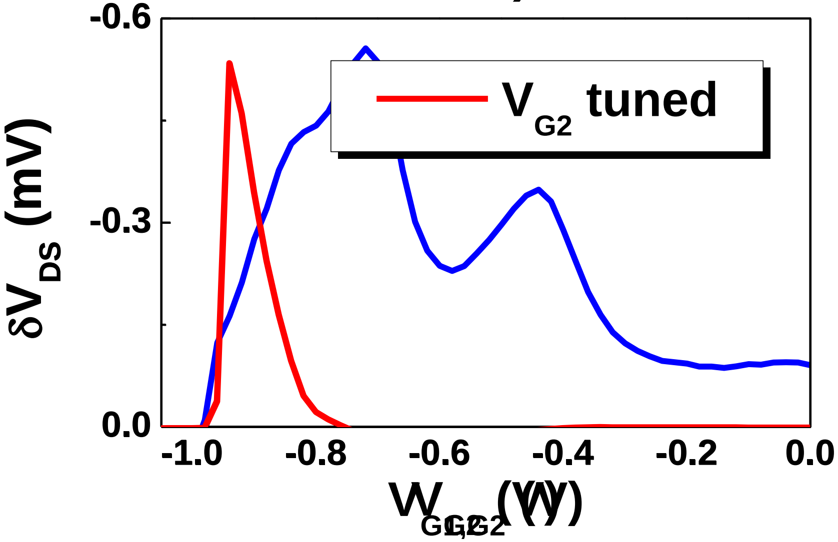
- **Detection**: depleted 2DEG
- **Coupling**: log-periodic antenna
- **Resonance**: 2D plasmon wavelength set by device geometry

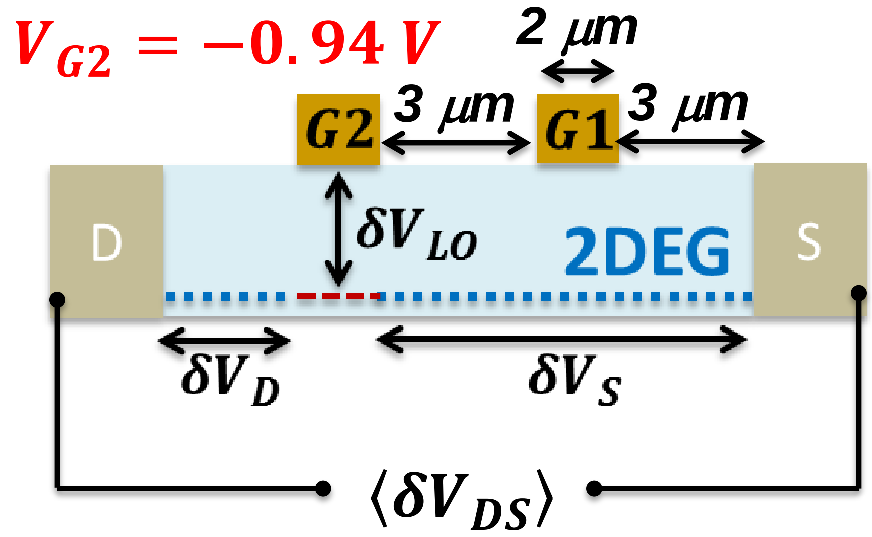


G.C. Dyer *et al.*, *Phys. Rev. Lett.* **109**, 126803 (2012) & G.C. Dyer *et al.*, *Appl. Phys. Lett.* **100**, 083506 (2012)

Single cavity & detector

270 GHz, 10 K



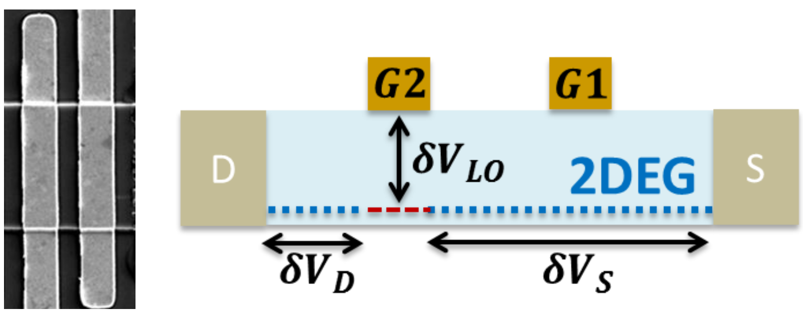


G.C. Dyer *et al.*, manuscript in preparation

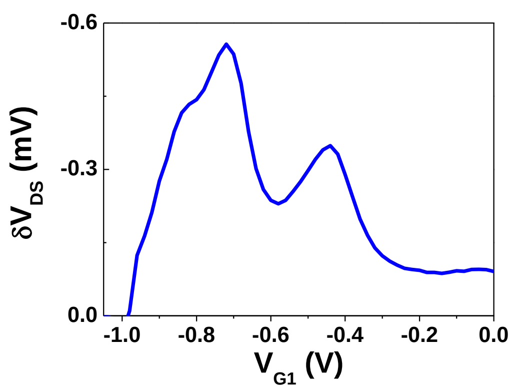
Plasmonic Spectroscopy

FIR Signal(s)

Detector + Plasmonic Cavity

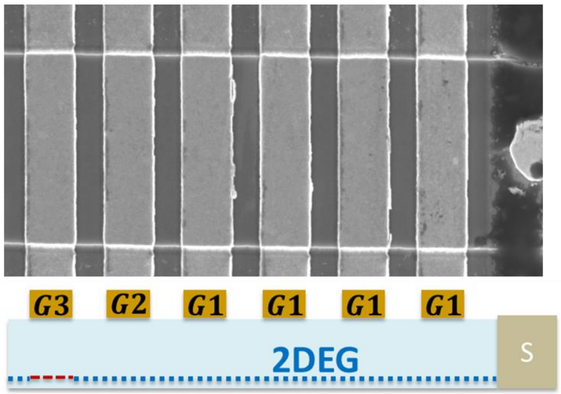


Spectrum of Incident Signal



Monochromatic FIR Source

Detector + Plasmonic Structure



Spectrum of Plasmonic Structure

???

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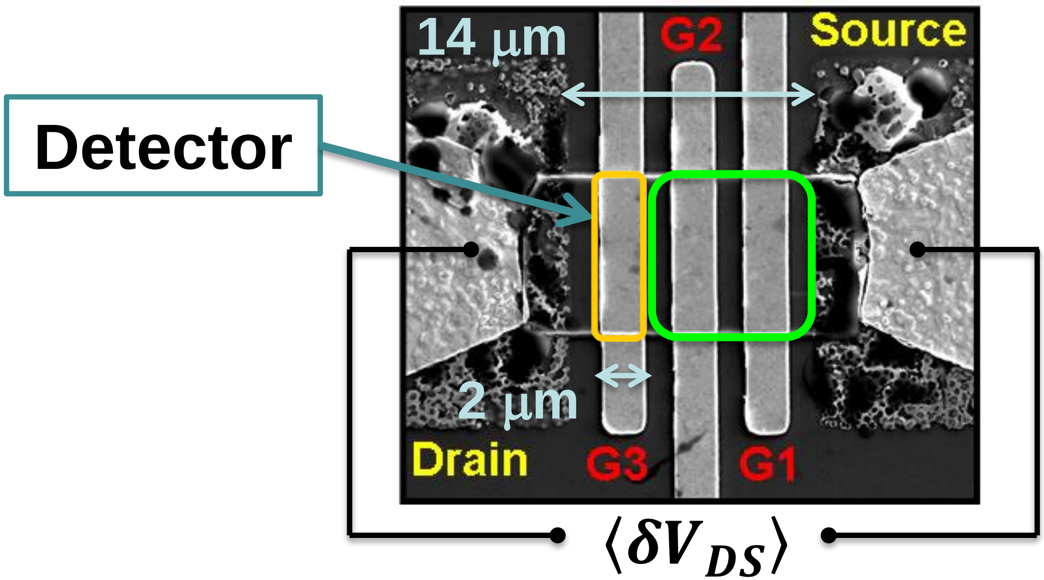
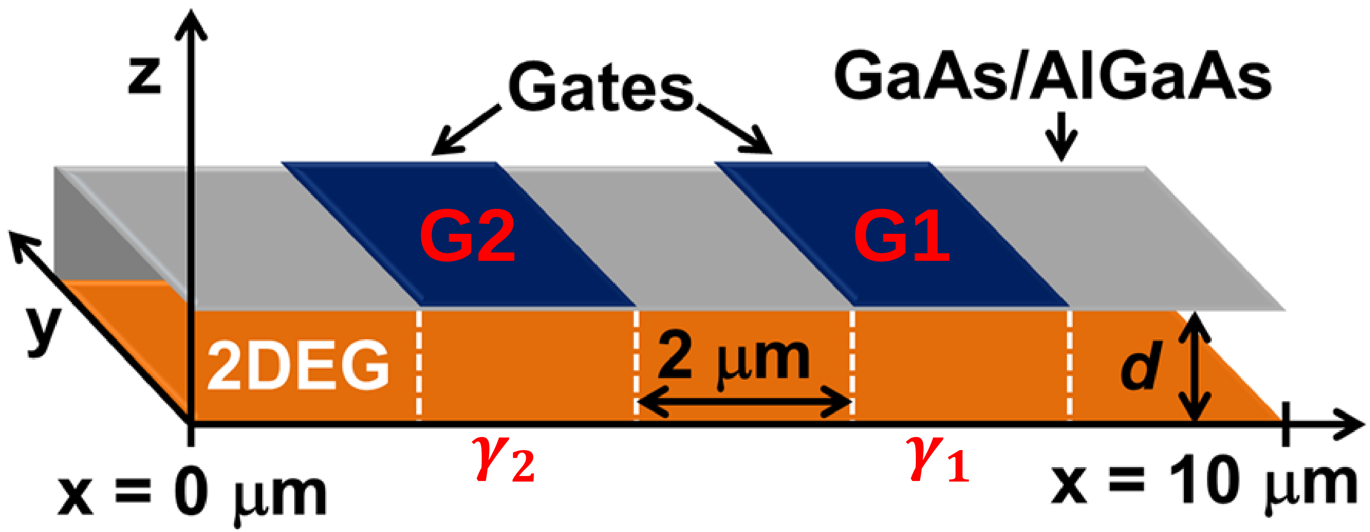
Inhomogeneous 2DEG Structures



Normalized 2DEG Density

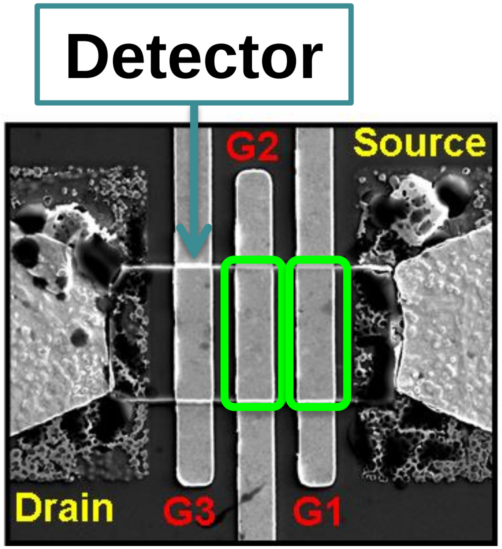
$$\gamma_1 = \frac{V_{th} - V_{G1}}{V_{th}}$$

$$\gamma_2 = \frac{V_{th} - V_{G2}}{V_{th}}$$



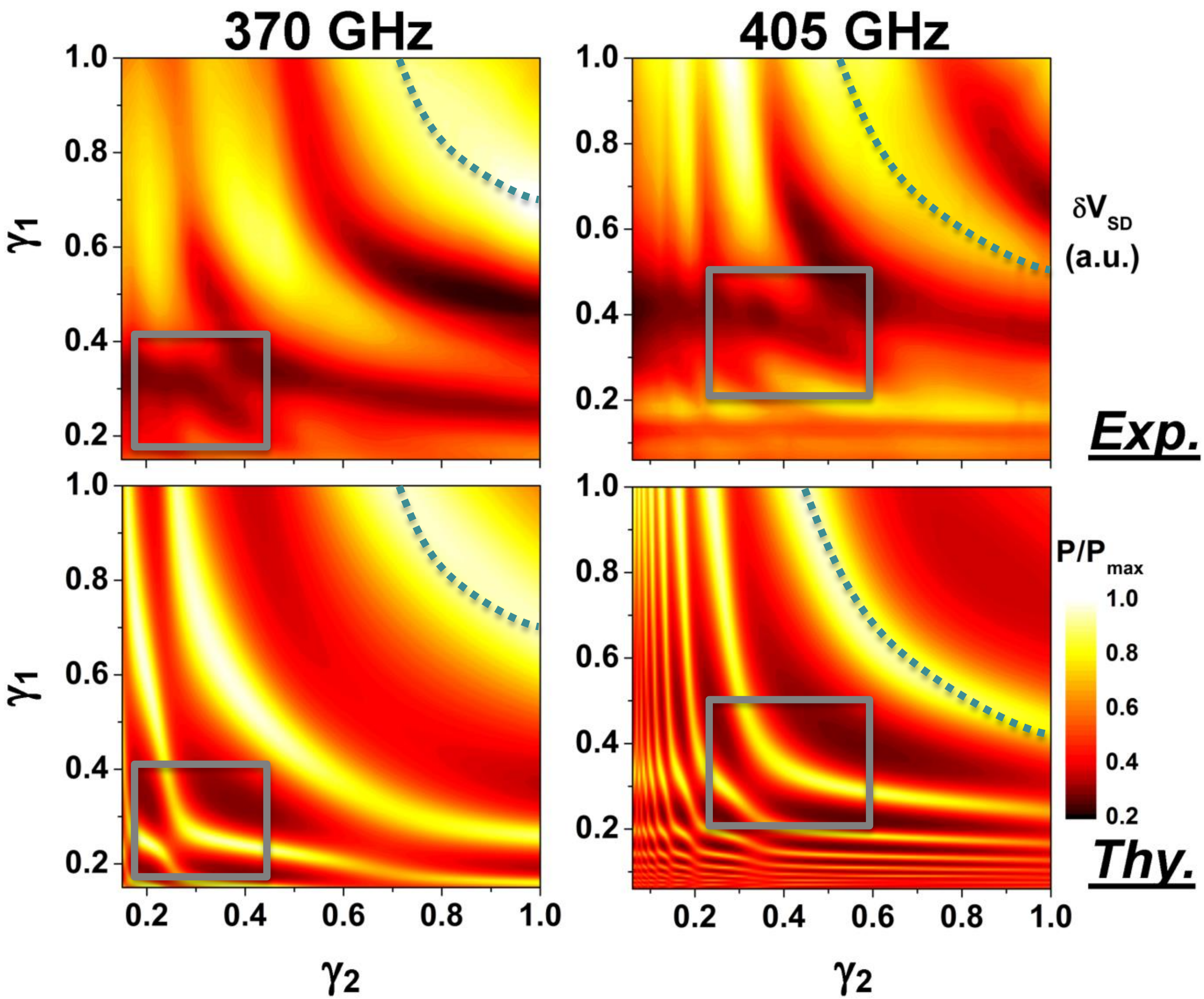
G.C. Dyer *et al.*, *Phys. Rev. Lett.* **109**, 126803 (2012) & G.C. Dyer *et al.*, *Appl. Phys. Lett.* **100**, 083506 (2012)

Coherent Plasmonic Coupling



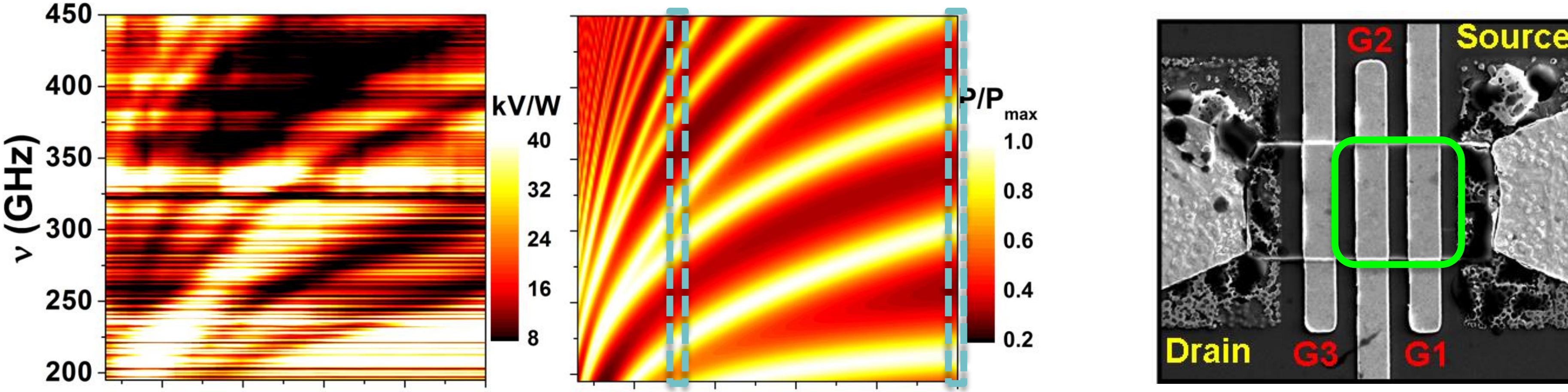
$$\gamma_{1,2} = \frac{V_{th} - V_{G1,G2}}{V_{th}}$$

Strongly coupled 2D plasmonic resonators



G.C. Dyer *et al.*, *Phys. Rev. Lett.* **109**, 126803 (2012)

Incipient Finite Plasmonic Crystal



Exp. ***Thy.***

$$\gamma = \gamma_1 = \gamma_2$$

Two period plasmonic crystal embedded in 10 μm plasmonic cavity

G.C. Dyer *et al.*, *Phys. Rev. Lett.* **109**, 126803 (2012)

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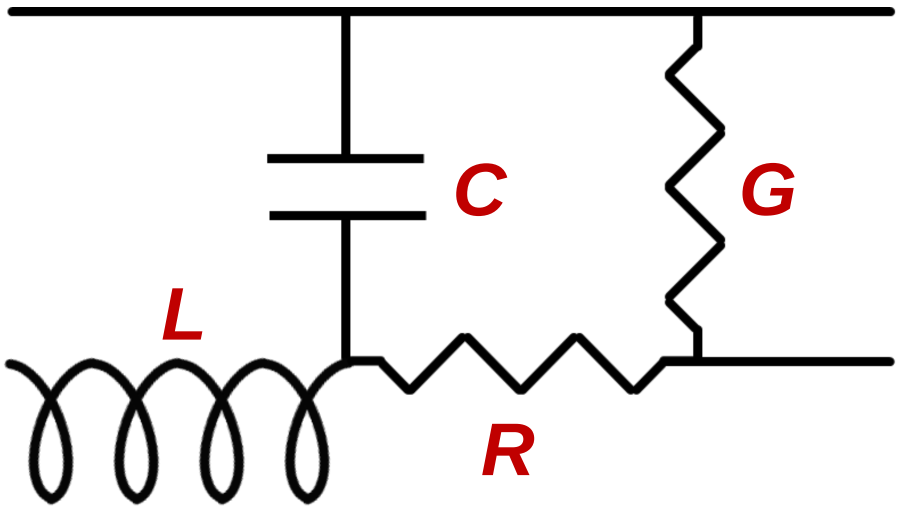
Transmission Line (TL) Theory



Telegrapher's Equations

$$\frac{\partial V(x)}{\partial x} + \left(R + L\frac{\partial}{\partial t}\right) I(x) = 0$$

$$\frac{\partial I(x)}{\partial x} + \left(G + C\frac{\partial}{\partial t}\right) V(x) = 0$$

Wave Solutions

$$V(x) = V_+ e^{-iqx} + V_- e^{+iqx}$$

$$I(x) = \frac{1}{Z_0}\left(V_+ e^{-iqx} - V_- e^{+iqx}\right)$$

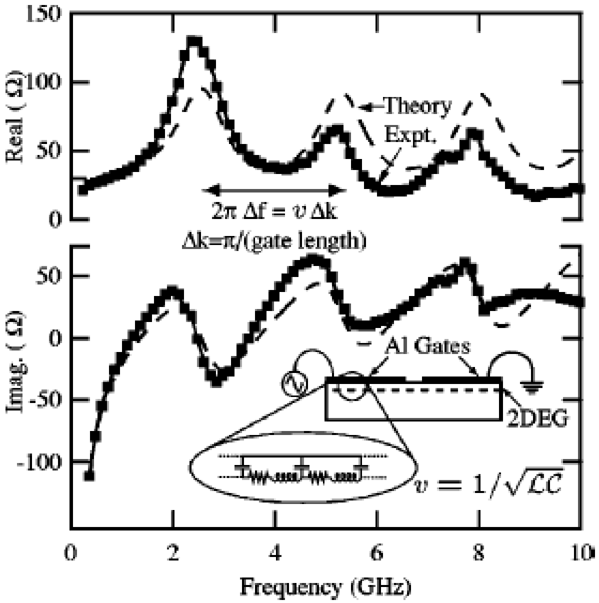
Characteristic Z & Dispersion

$$Z_0 = \sqrt{\frac{R + i\omega L}{G + i\omega C}}$$

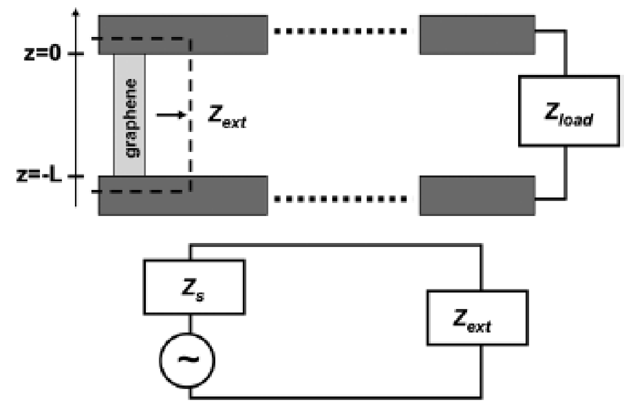
$$iq = \sqrt{(R + i\omega L)(G + i\omega C)}$$

Plasmonic TL Model

High frequency conductivity of the high-mobility two-dimensional electron gas



Graphene Terahertz Plasmon Oscillators



$$Z_0 = \sqrt{\frac{Z_{2DEG}}{i\omega C(\omega)}}$$

$$iq = \sqrt{i\omega C(\omega) Z_{2DEG}}$$

$$Z_{2DEG} = \frac{m^*}{e^2 n_{2D} \tau W}(1 + i\omega\tau)$$

$$\lim_{qd\to 0} C(\omega) = \frac{W\epsilon}{d}$$

(fully screened limit)

from Drude model Im[Z_{2DEG}] is <u>kinetic inductance</u>

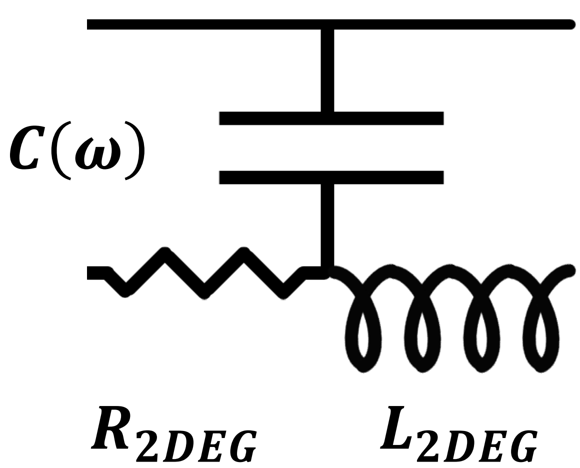
$$\lim_{qd\to\infty} C(\omega) = 2W\epsilon q$$

(unscreened limit)

P. J. Burke *et al.*, *APL* **76**, 745 (2000)

F. Rana, *IEEE Trans. on Nanotechnology* **7**, 91 (2008)

Generalized Plasmonic TL Model



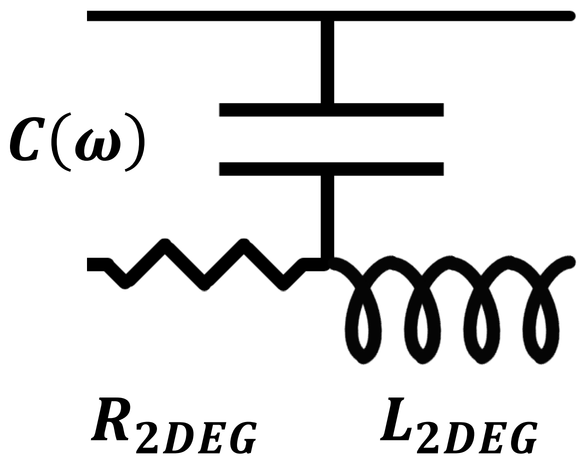
$$C(\omega) = \frac{\delta n(x)}{\delta \Phi(x, z = 0)} = W\epsilon q(1 + coth[qd])$$

$$\frac{1}{2}\tilde{V}(x)\tilde{I}^*(x) = \frac{1}{2}\Phi(x,0)I^*(x)\ \chi^*(\omega, d)$$

$$\tilde{V}(x) \equiv \Phi(x,0)$$
$$\tilde{I}(x) \equiv I(x)\chi(\omega, d)$$

G.C. Dyer *et al.*, *Phys. Rev. Lett.* **109**, 126803 (2012)

Generalized Plasmonic TL Model



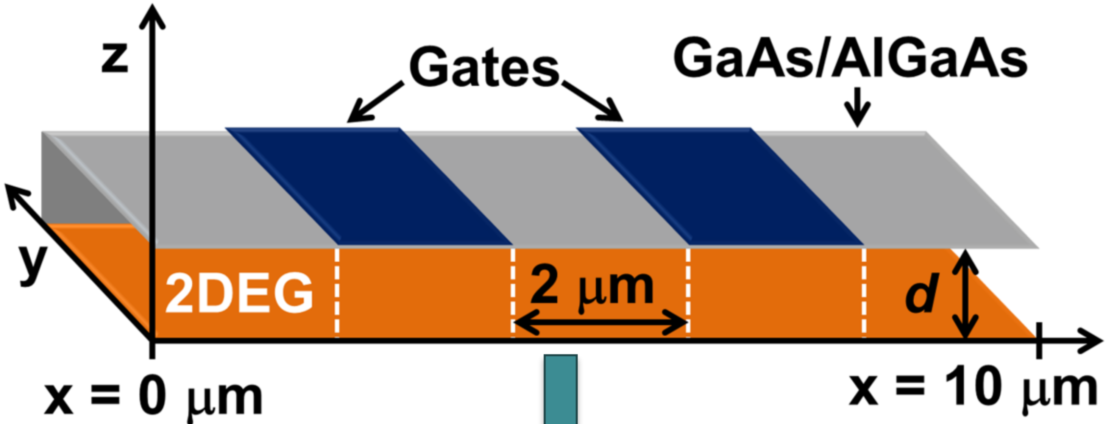
$$C(\omega) = W\epsilon q(1 + \coth[qd])$$
$$L_{2DEG} = \frac{m^*}{e^2 n_{2D} W}$$
$$R_{2DEG} = L_{2DEG}/\tau$$

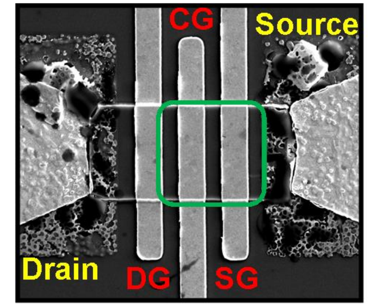
$$Z = \frac{1}{\chi(\omega, d)} \sqrt{\frac{R_{2DEG} + i\omega L_{2DEG}}{i\omega C(\omega)}}$$
$$q = -i\sqrt{i\omega C(\omega)(R_{2DEG} + i\omega L_{2DEG})}$$

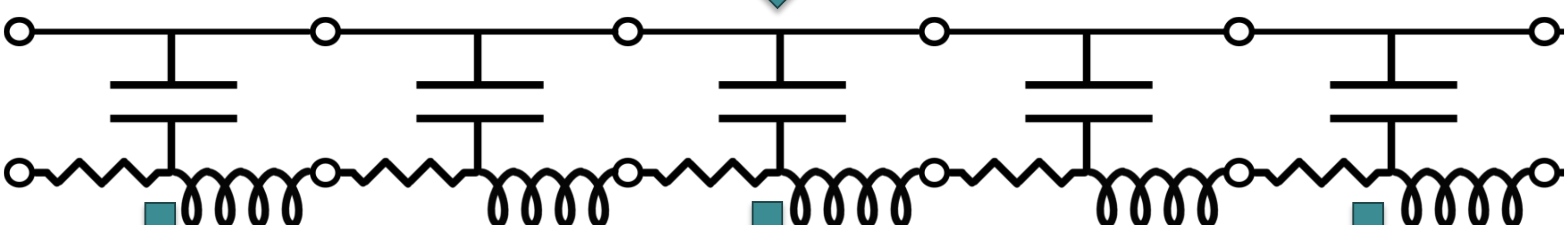
where: $\chi(\omega, d) = 1 - \frac{q\left(1 - e^{-2q'd}\cos[2q''d]\right)}{2q'\left(1 - e^{-2q^*d}\right)} + \frac{q\, e^{-2q'd}\sin[2q''d]}{2q''\left(1 - e^{-2q^*d}\right)}$

G.C. Dyer *et al.*, *Phys. Rev. Lett.* **109**, 126803 (2012)

Discretized Plasmonic TL





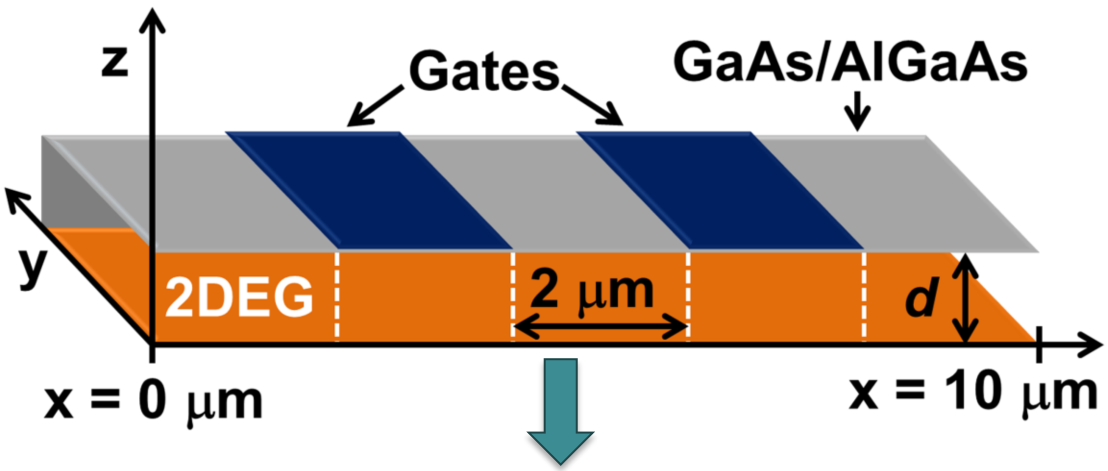


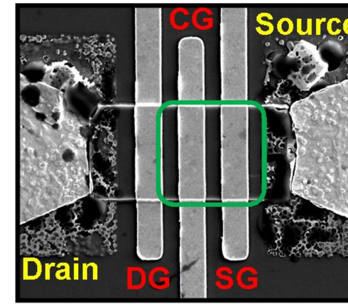
$$\begin{pmatrix} \cos[q_1 a_1] & i\tilde{Z}_1 \sin[q_1 a_1] \\ i\sin[q_1 a_1]/\tilde{Z}_1 & \cos[q_1 a_1] \end{pmatrix} \quad \begin{pmatrix} \cos[q_3 a_3] & i\tilde{Z}_3 \sin[q_3 a_3] \\ i\sin[q_3 a_3]/\tilde{Z}_3 & \cos[q_3 a_3] \end{pmatrix} \quad \begin{pmatrix} \cos[q_5 a_5] & i\tilde{Z}_5 \sin[q_5 a_5] \\ i\sin[q_5 a_5]/\tilde{Z}_5 & \cos[q_5 a_5] \end{pmatrix}$$

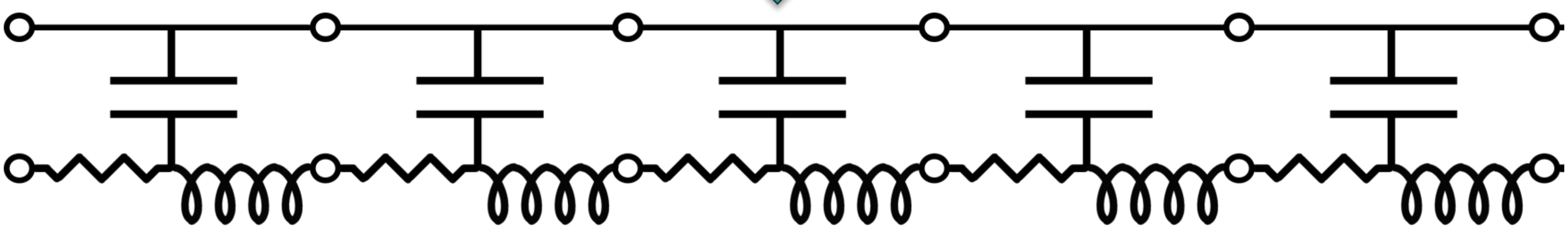
$$\begin{pmatrix} \cos[q_2 a_2] & i\tilde{Z}_2 \sin[q_2 a_2] \\ i\sin[q_2 a_2]/\tilde{Z}_2 & \cos[q_2 a_2] \end{pmatrix} \quad \begin{pmatrix} \cos[q_4 a_4] & i\tilde{Z}_4 \sin[q_4 a_4] \\ i\sin[q_4 a_4]/\tilde{Z}_4 & \cos[q_4 a_4] \end{pmatrix}$$

G.R. Aizin and G.C. Dyer, *Phys. Rev. B* **86**, 235316 (2012)

Discretized Plasmonic TL







Solution for an inhomogeneous cavity with step-like boundaries between TL elements is reduced to linear algebra:

$$\begin{pmatrix} \tilde{V}_m \\ \tilde{I}_m \end{pmatrix} = \left[\prod_m^n \begin{pmatrix} \cos[q_m a_m] & i\tilde{Z}_m \sin[q_m a_m] \\ i\sin[q_m a_m] / \tilde{Z}_m & \cos[q_m a_m] \end{pmatrix} \right] \begin{pmatrix} \tilde{V}_{n+1} \\ \tilde{I}_{n+1} \end{pmatrix}$$

G.R. Aizin and G.C. Dyer, *Phys. Rev. B* **86**, 235316 (2012)

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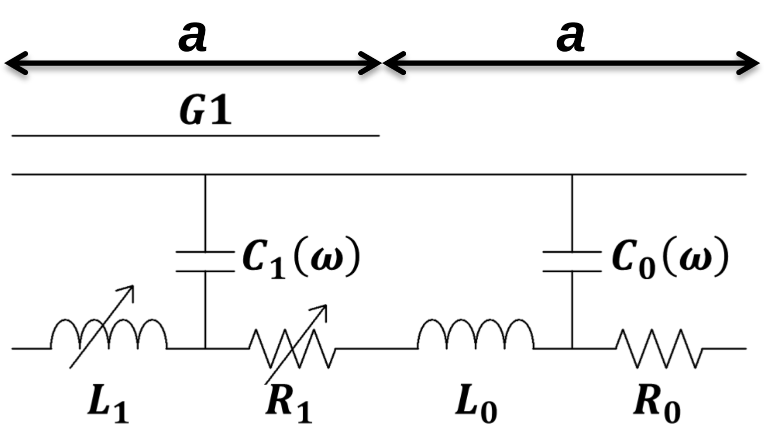
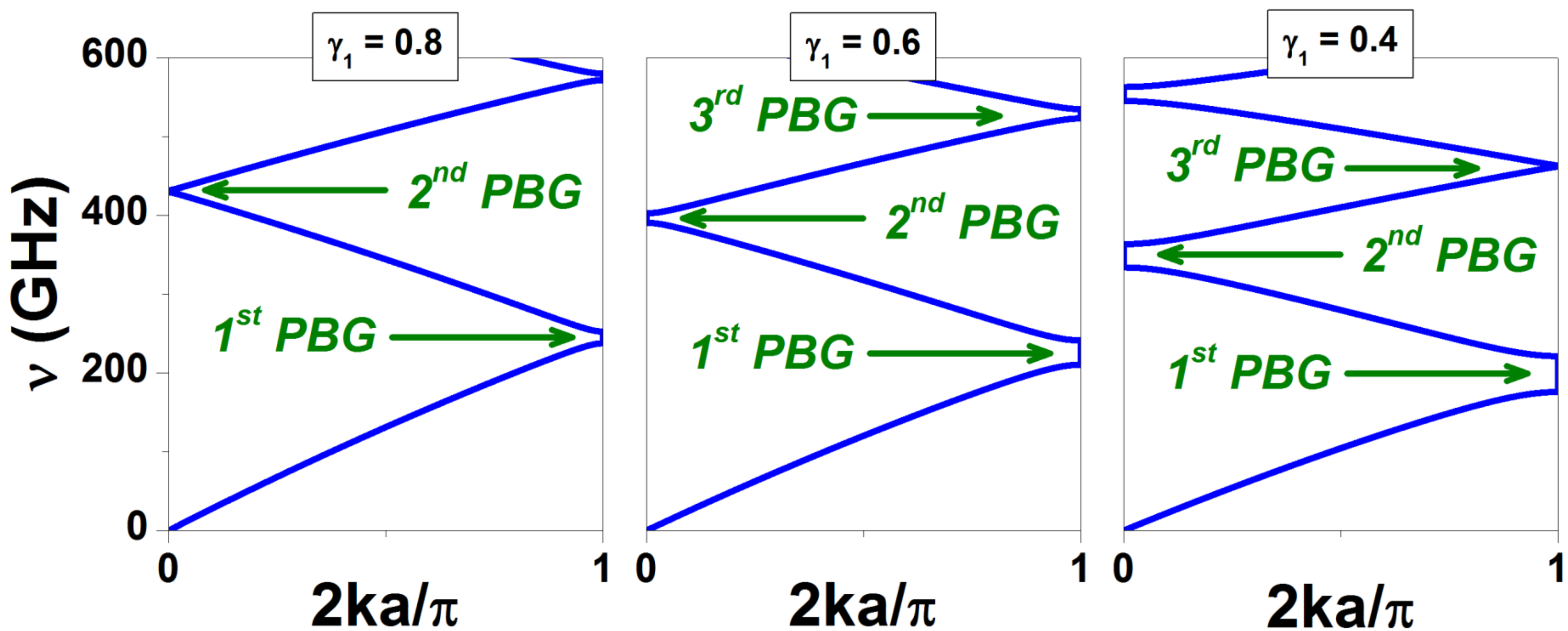
  - Electromagnetically induced transparency
- Conclusions & future directions

Plasmonic Crystal Band Structure



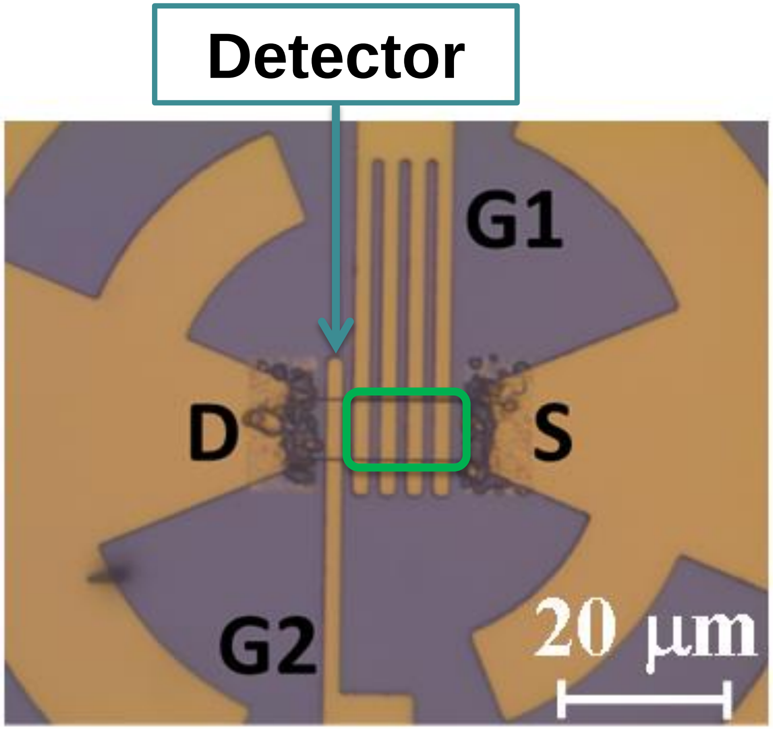
1D Kronig-Penney:

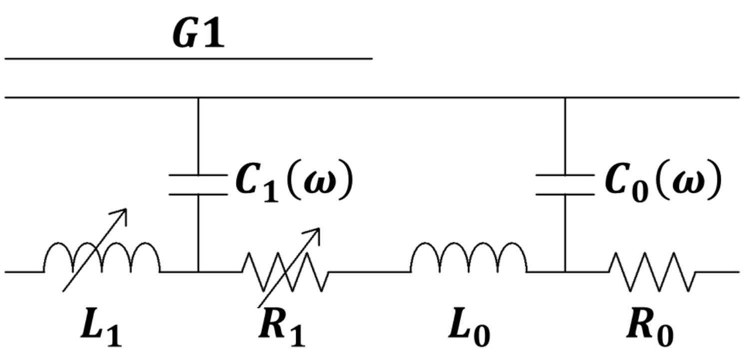
$$\cos 2k_B a = \cos q_0 a \cos q_1 a - \frac{1}{2}\left(\frac{Z_0}{Z_1} + \frac{Z_1}{Z_0}\right) \sin q_0 a \sin q_1 a$$

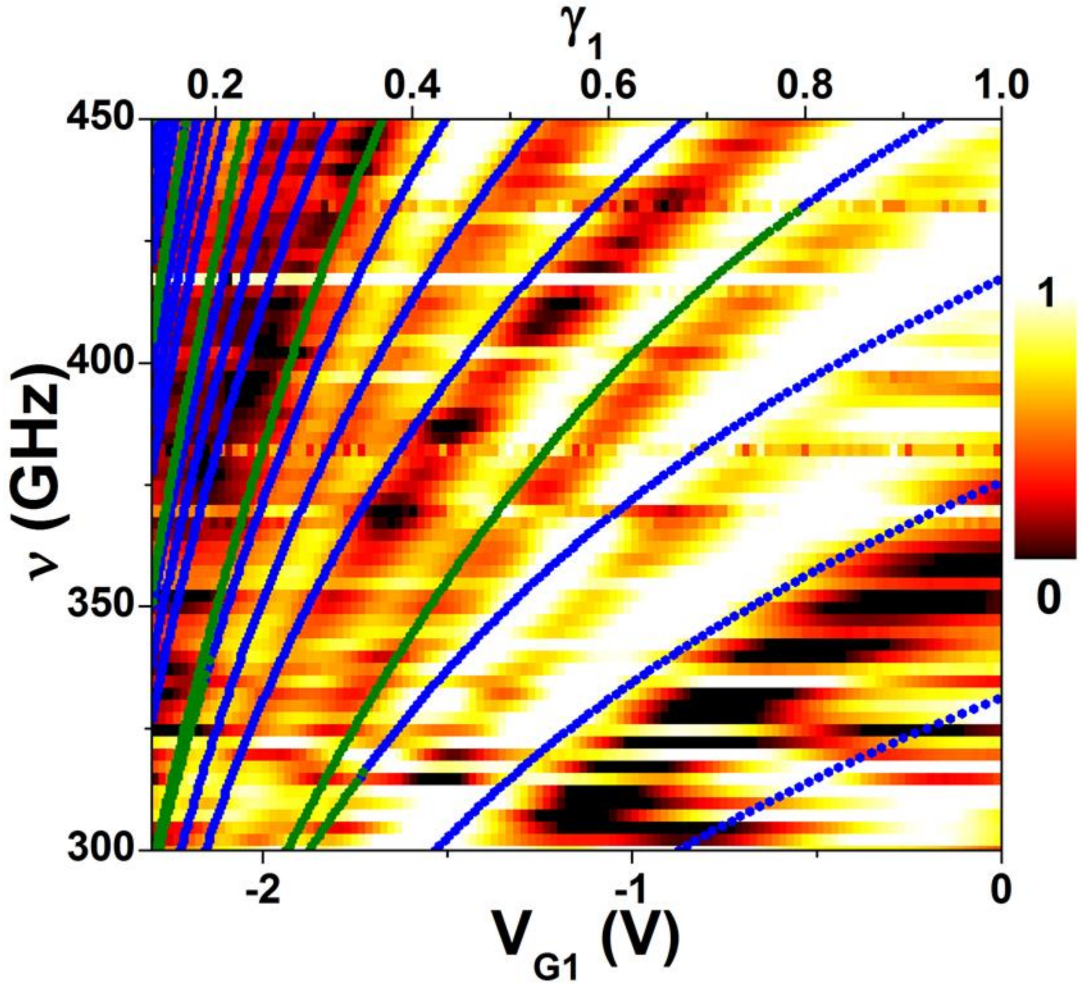


G.C. Dyer *et al.*, *Nature Photonics*, DOI: 10.1038/NPHOTON.2013.252 (2013)

Four Period Plasmonic Crystal



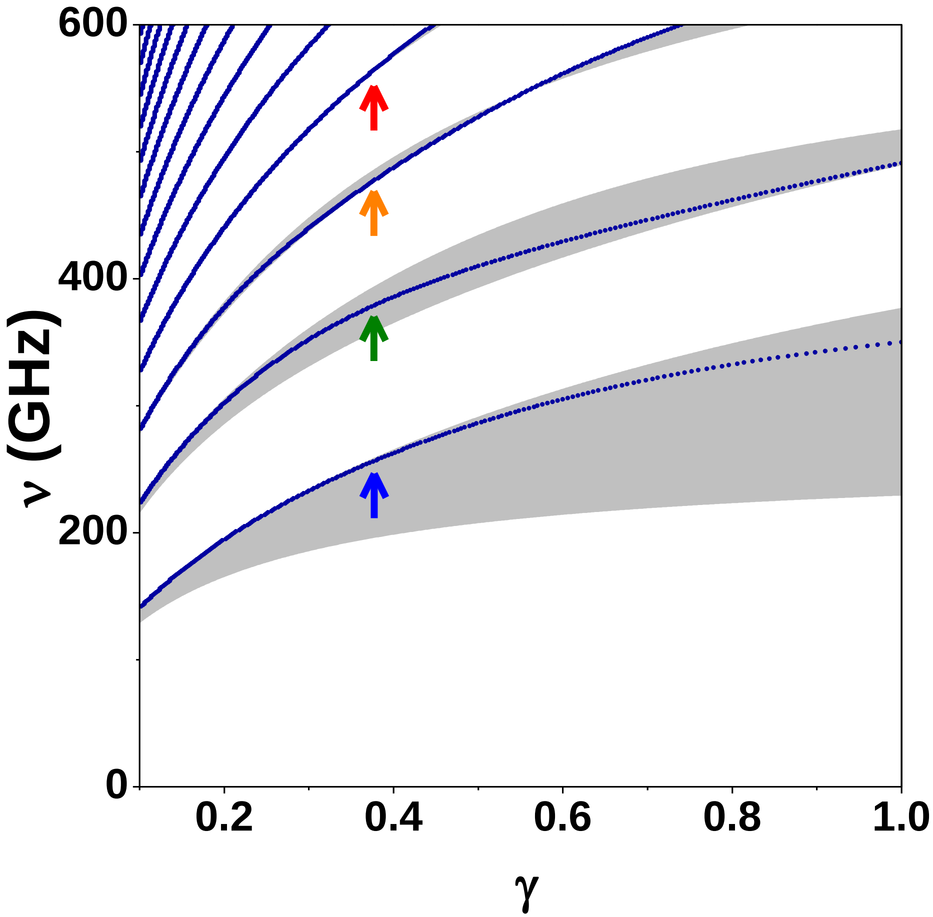


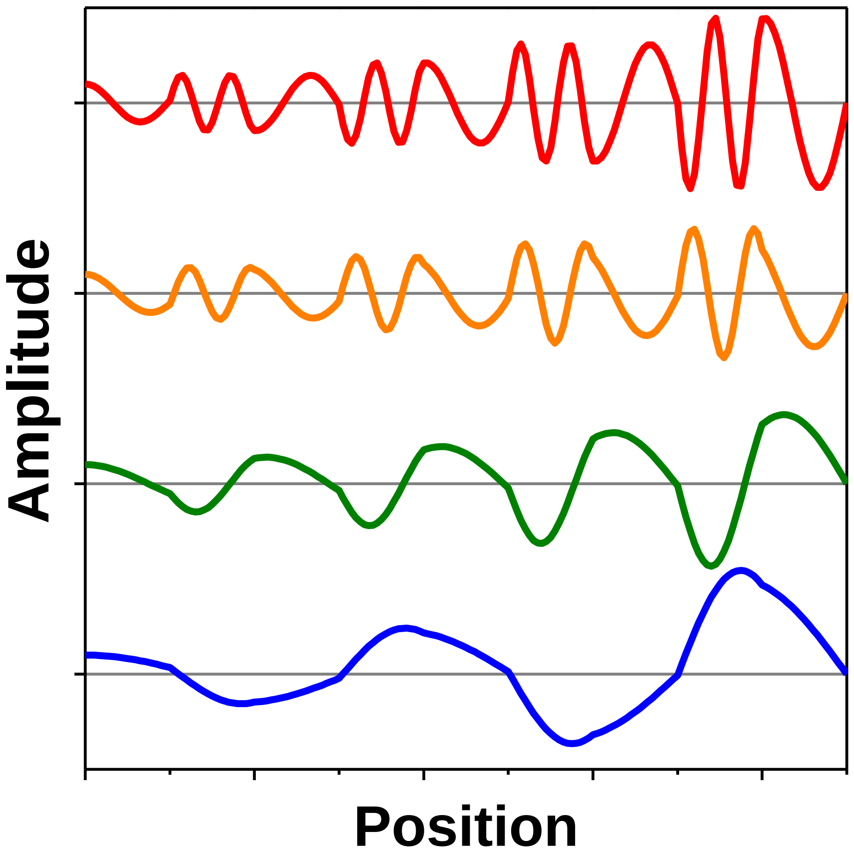


$$V_{G1} \rightarrow 0, L_1 \rightarrow \infty$$

G.C. Dyer *et al.*, *Nature Photonics*, DOI: 10.1038/NPHOTON.2013.252 (2013)

Plasmonic Tamm States

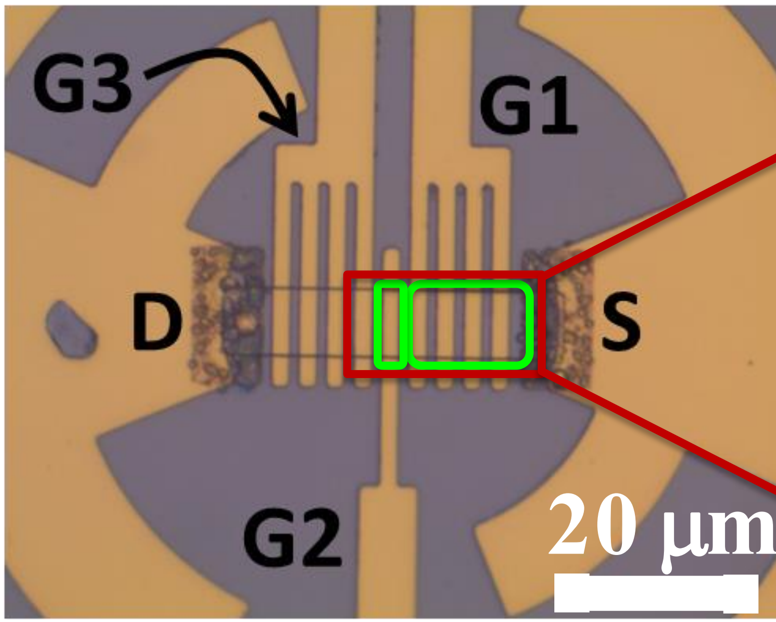


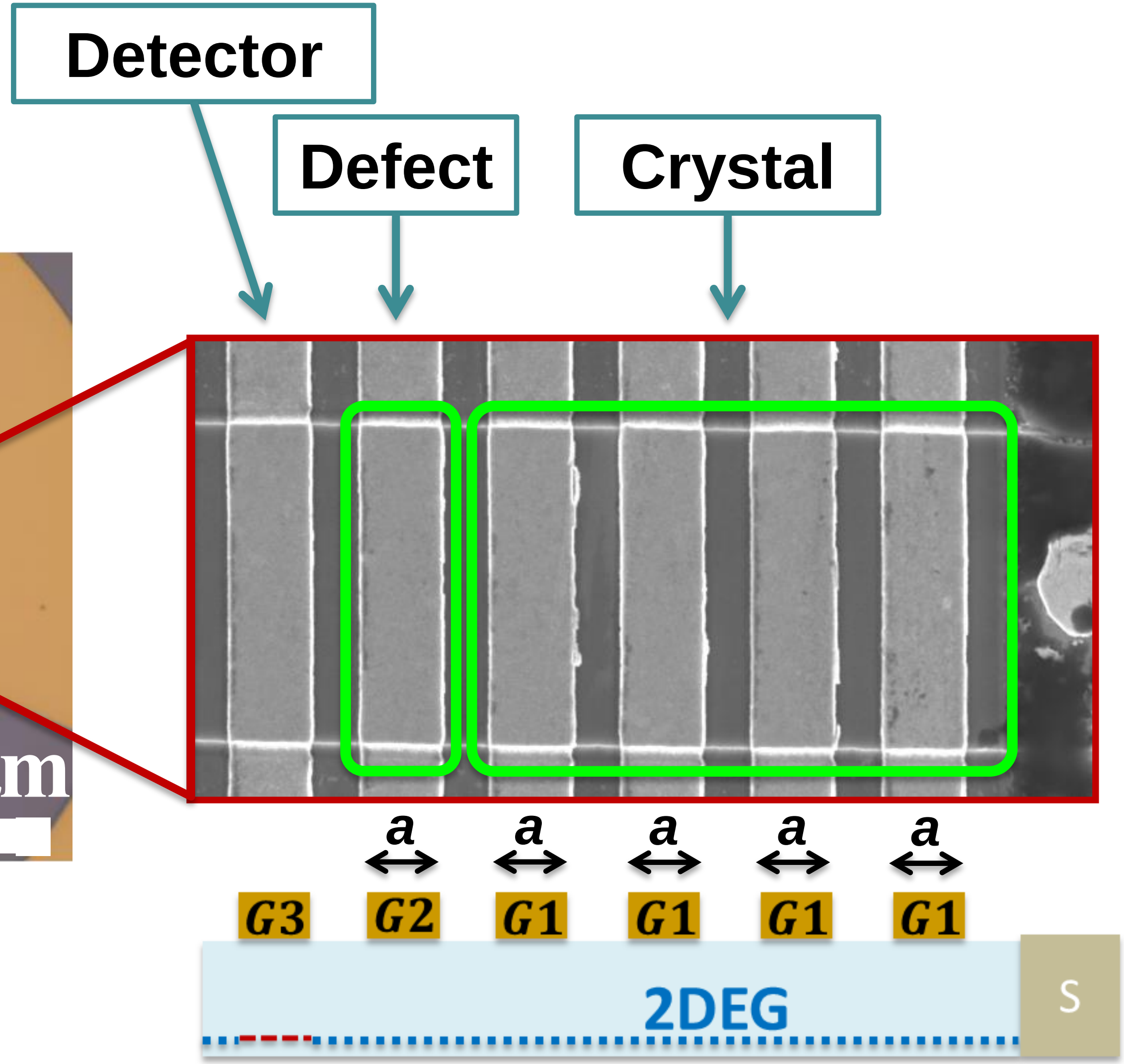


Crystal surface states typically found in crystal band gap that have complex Bloch wavevector ($Im[k_B] \neq 0$)

G.R. Aizin and G.C. Dyer, *Phys. Rev. B* **86**, 235316 (2012)

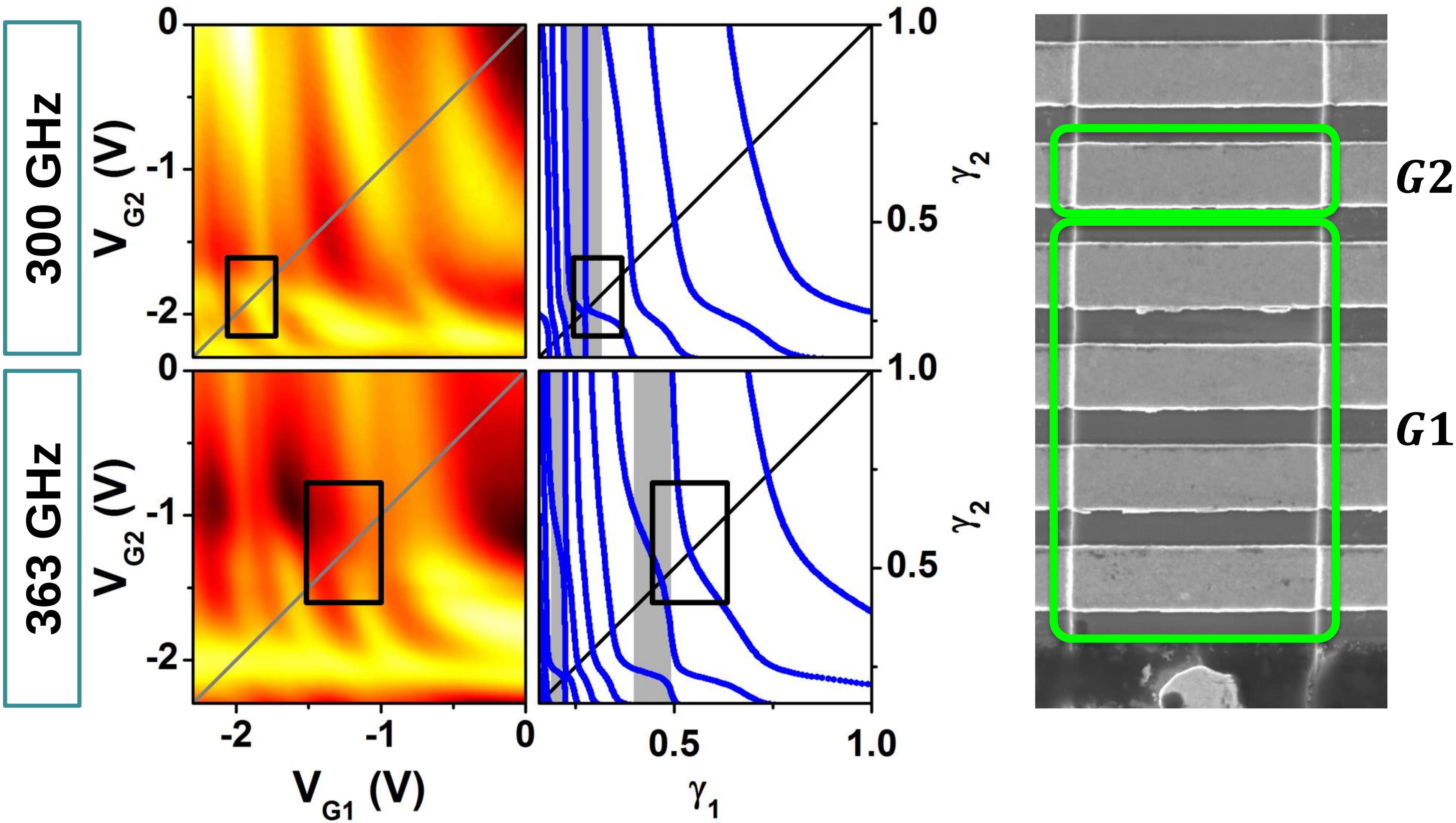
Defect Probing of Tamm States





G.C. Dyer *et al.*, *Nature Photonics*, DOI: 10.1038/NPHOTON.2013.252 (2013)

Coupled Tamm & Defect States



G.C. Dyer *et al.*, *Nature Photonics*, DOI: 10.1038/NPHOTON.2013.252 (2013)

Paired Tamm States

Sandia National Laboratories

On the Surface States Associated with a Periodic Potential

WILLIAM SHOCKLEY
Bell Telephone Laboratories, New York, New York

(Received June 19, 1939)

Tamm found in this case that it was possible to have energy levels whose wave functions were localized at the surface of the crystal. In this treatment a semi-infinite crystal was used, and Tamm found that one surface level was possible for each energy gap between the ordinary allowed bands of energies. In a later paper Fowler[3] discussed Tamm's levels for a finite crystal and pointed out that the levels should occur in pairs because of the two faces of the crystal. They

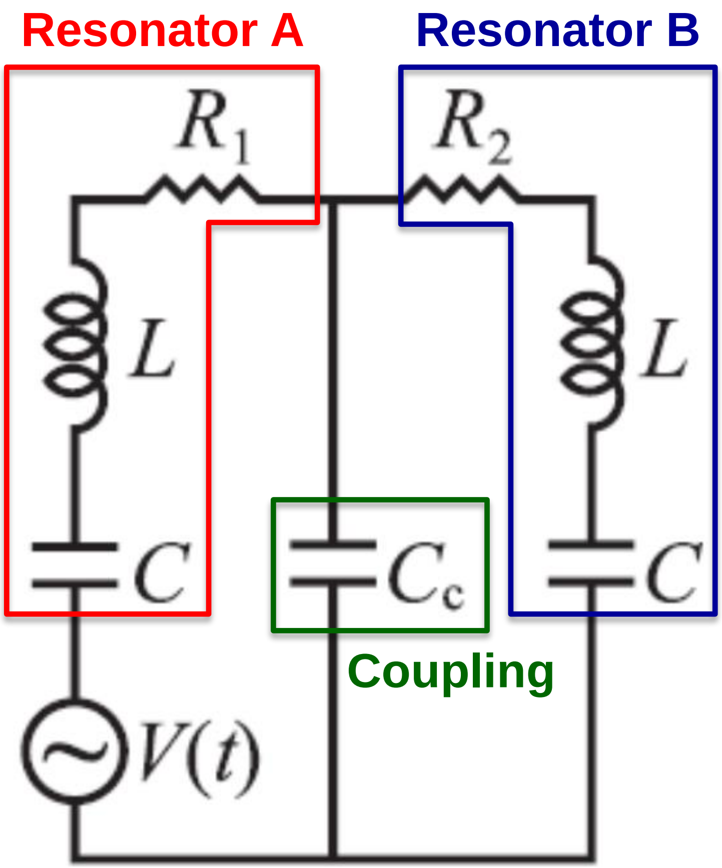
W. Shockley, *Physical Review* **56**, 317-323 (1939)

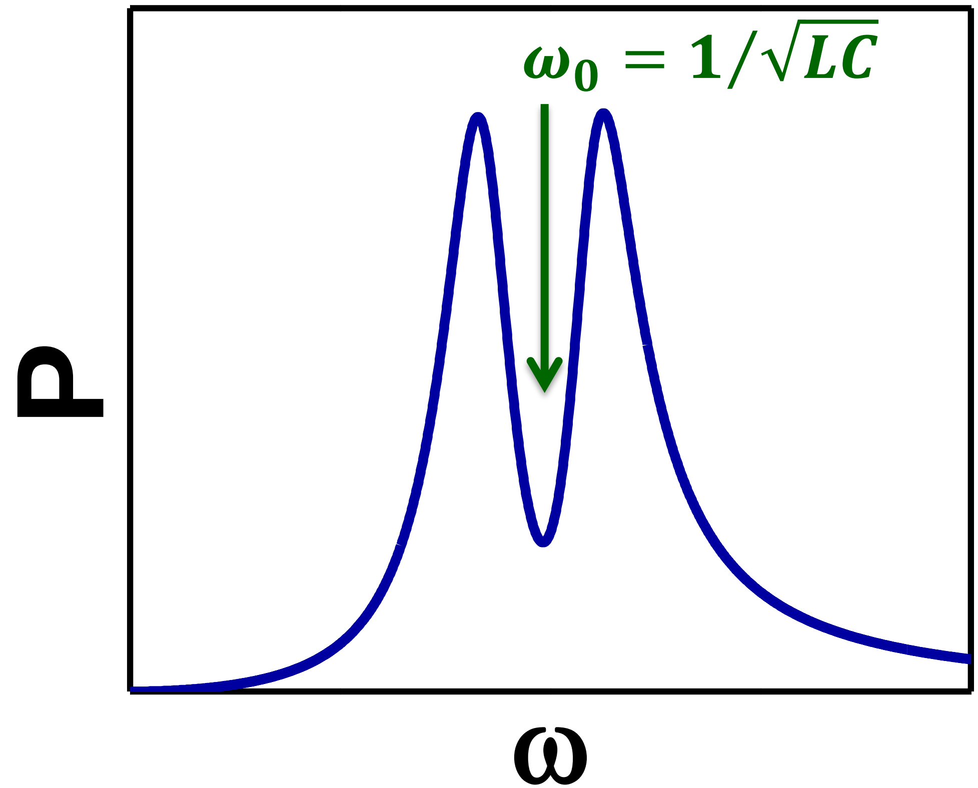
Outline

- Introduction
- Low dimensional far infrared plasmonic structures
  - Integrated 2D plasmonic devices
  - Strong coupling of tunable 2D plasmonic resonators
  - Generalized 2D plasmonic transmission line model
  - Active control of plasmonic crystal band structure
  - **Electromagnetically induced transparency**
- Conclusions & future directions

Classical Analogue of EIT

“Low-Loss Metamaterials Based on Classical Electromagnetically Induced Transparency”





$$P = \mathrm{Re}\frac{i\omega\frac{V^2}{2}(L\omega^2 - iR_2\omega - \frac{1}{C_\parallel})}{\frac{1}{C_c^2} - (L\omega^2 - iR_2\omega - \frac{1}{C_\parallel})(L\omega^2 - iR_1\omega - \frac{1}{C_\parallel})}$$

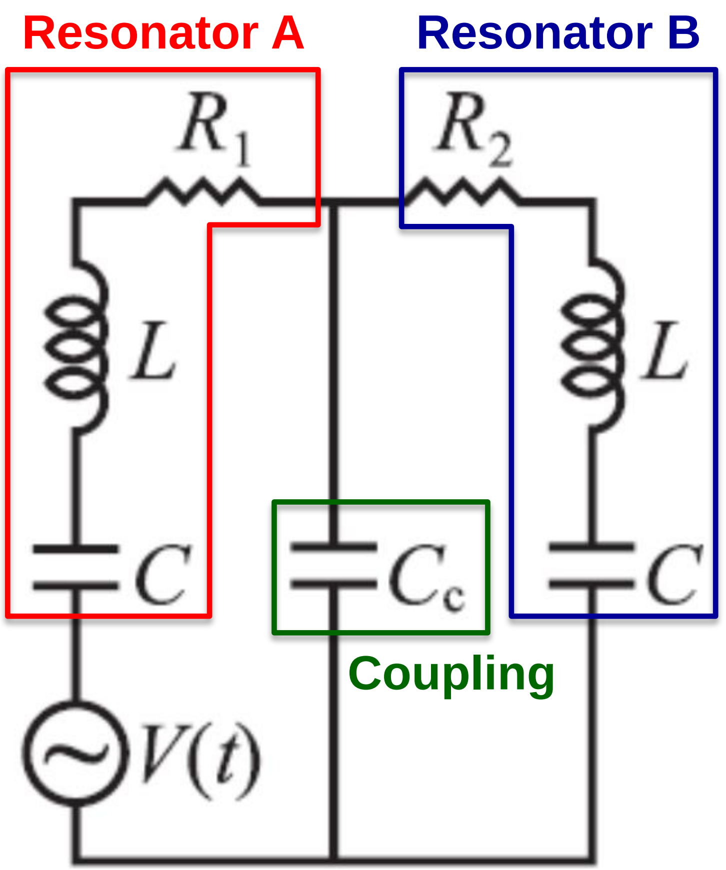
with $C_\parallel = (1/C + 1/C_c)^{-1}$

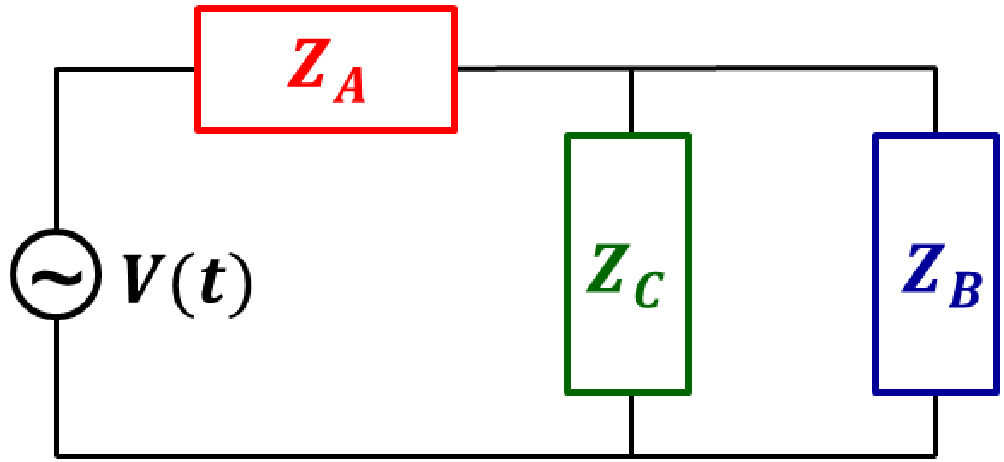
P. Tassin *et. al.*, *Phys. Rev. Lett.* **102**, 053901 (2009)

Classical Analogue of EIT

"Low-Loss Metamaterials Based on Classical Electromagnetically Induced Transparency"

$$Z_A = R_1 + \frac{1 - \omega^2 LC}{i\omega C}$$





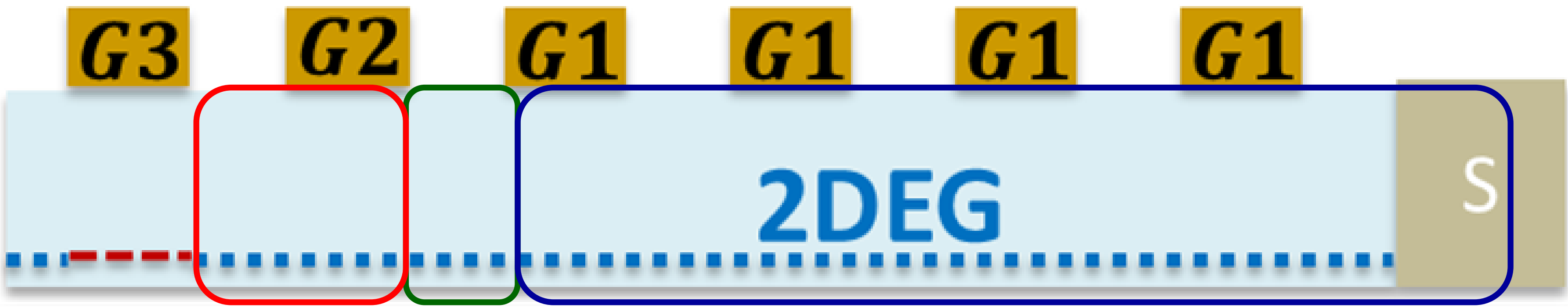
$$Z_C = \frac{1}{i\omega C_C}$$

$$Z_B = R_2 + \frac{1 - \omega^2 LC}{i\omega C}$$

$$Z_{eq} = Z_A + \frac{Z_B Z_C}{Z_B + Z_C}$$

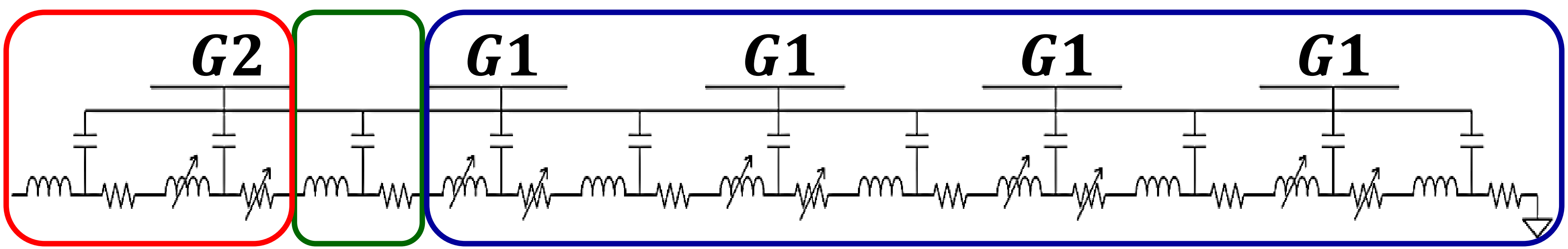
P. Tassin *et. al.*, *Phys. Rev. Lett.* **102**, 053901 (2009)

Plasmonic Crystal-Defect EIT



Resonator A:
Defect Mode

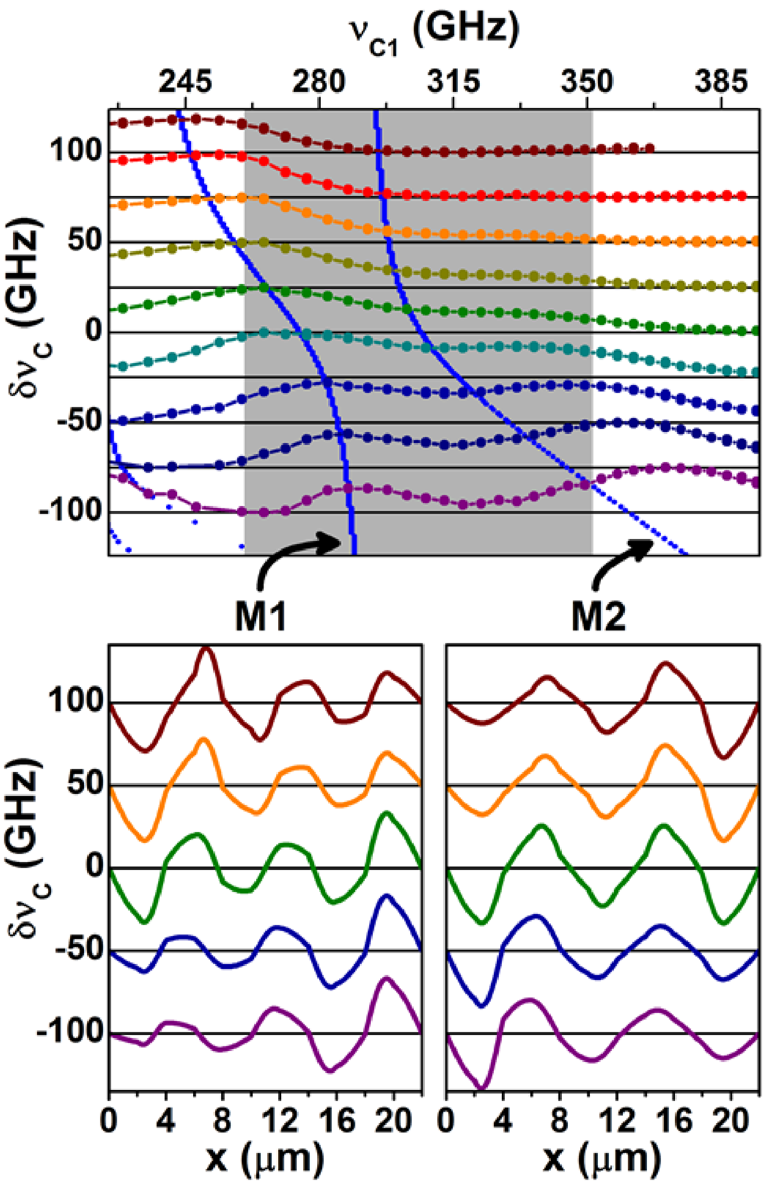
Resonator B:
Localized Crystal Tamm State



Coupling

G.C. Dyer *et al.*, *Nature Photonics,* DOI: 10.1038/NPHOTON.2013.252 (2013)

Active Control of Plasmonic EIT

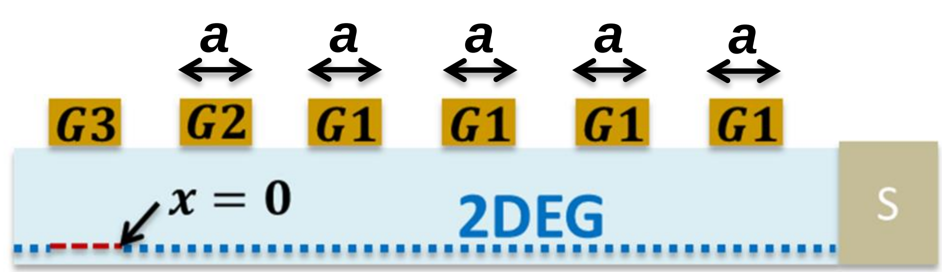


Crystal-defect eigenmodes in or near crystal band gap at **210 GHz**

$$\nu_{Cj} = \frac{\beta_C}{2\pi\sqrt{L_j C_j}}$$

$$\beta_C = \pi/a$$

$$\delta\nu_C = \nu_{C2} - \nu_{C1}$$



G.C. Dyer *et al.*, *Nature Photonics*, DOI: 10.1038/NPHOTON.2013.252 (2013)

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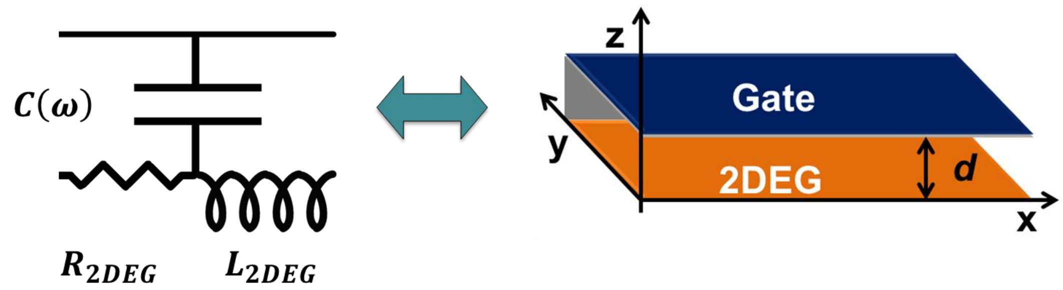
  - Electromagnetically induced transparency
- **Conclusions & future directions**

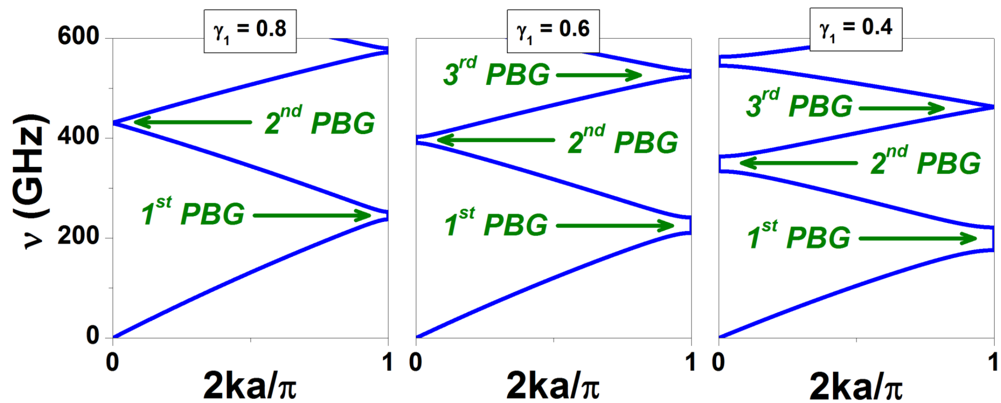
Conclusions

Sandia National Laboratories

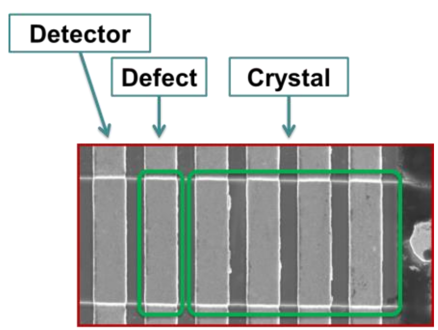
Plasmonic waveguide

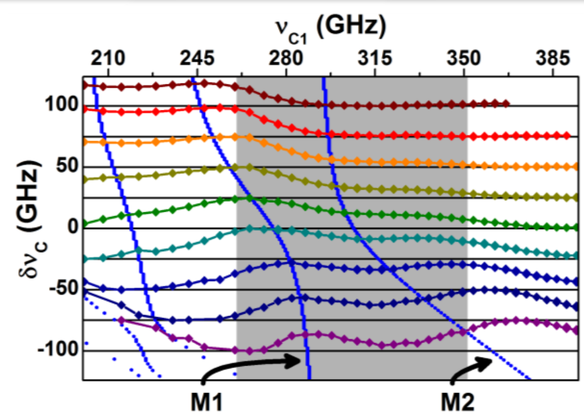


Active control of plasmonic dispersion



Monolithically integrated & reconfigurable





Credits

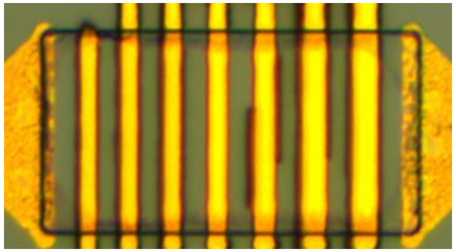
- Low dimensional plasmonics
  - **Grower:** John Reno
  - **Device Design/Mask Layout**: Greg Dyer, Eric Shaner
  - **Processing**: Eric Shaner, Don Bethke
  - **Characterization**: Greg Dyer, Albert Grine
  - **Data Analysis**: Greg Dyer
  - **Numerical Modeling**: Greg Dyer, Greg Aizin, John Mikalopas
  - **Theory**: Greg Aizin, Greg Dyer
  - **Funding**: Eric Shaner (STTR, BES), Joel Hensley (STTR)
- THz transceivers
  - **Grower:** John Reno
  - **Device Design/Mask Layout**: Mike Wanke, Chris Nordquist, Mike Cich, Mark Lee, Eric Young
  - **Processing**: Mike Cich, Melissa Cavaliere
  - **Characterization**: Greg Dyer, Mike Wanke, Albert Grine, Chuck Fuller, Mark Lee, Eric Young
  - **Data Analysis**: Greg Dyer, Mike Wanke
  - **Funding**: Mike Wanke (LDRD)

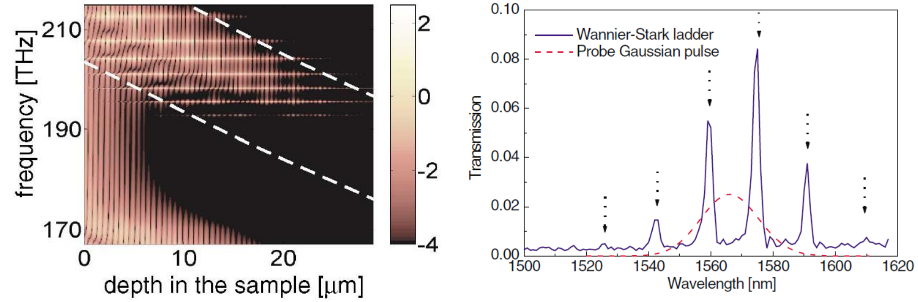
ADDITIONAL MATERIAL

Quantum & photonic analogues

Sandia National Laboratories

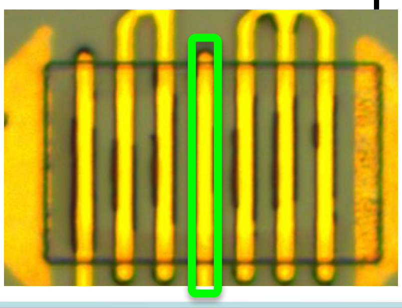
- Wannier-Stark ladder

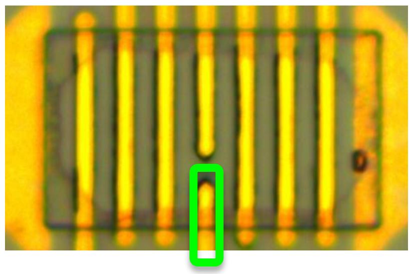


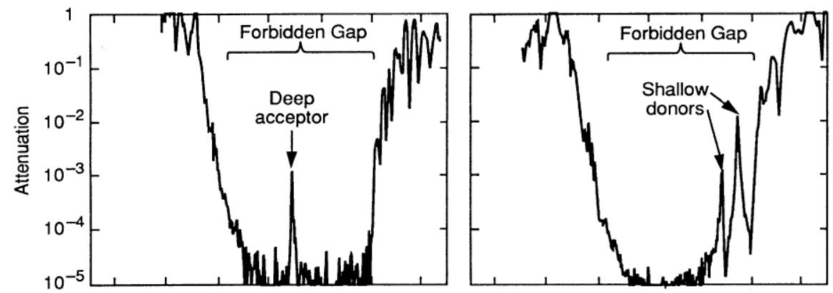


R. Sapienza *et al. PRL* **91**, 263902 (2003)

- Defect morphology & location

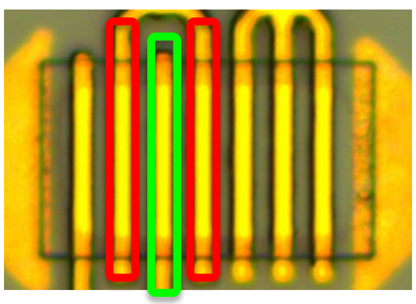


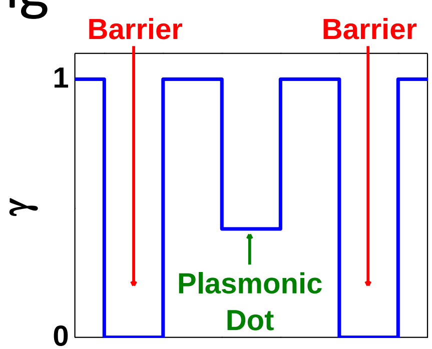


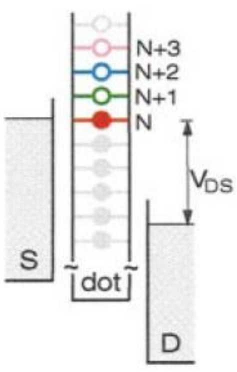


E. Yablonovitch *et al*. *PRL* **67**, 3380-3383 (1991)

- Plasmonic 'tunnel' coupling







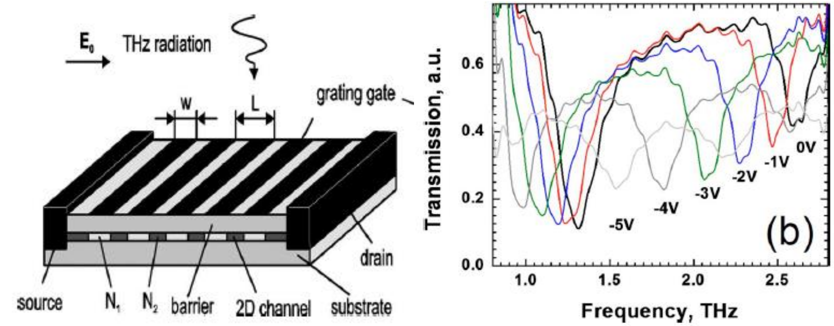
D.R. Stewart *et al. Science* **278**, 1784-1788 (1997)

Device images provided by Don Bethke. Thanks Don!

Potential material systems

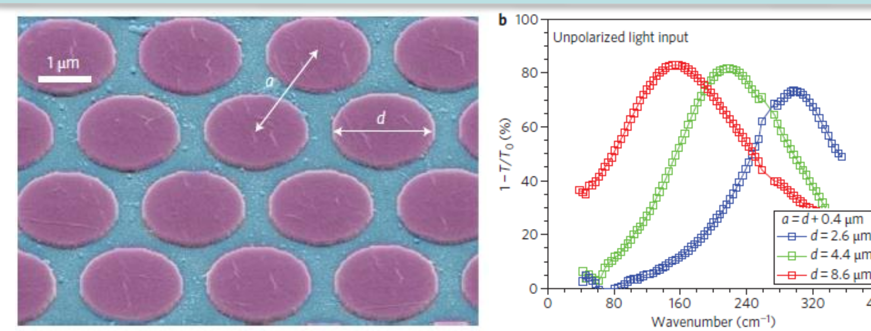
Sandia National Laboratories

- Nitride 2DEGs
  - >1 THz, > 77 K
  - Damping: phonon energies, coupling



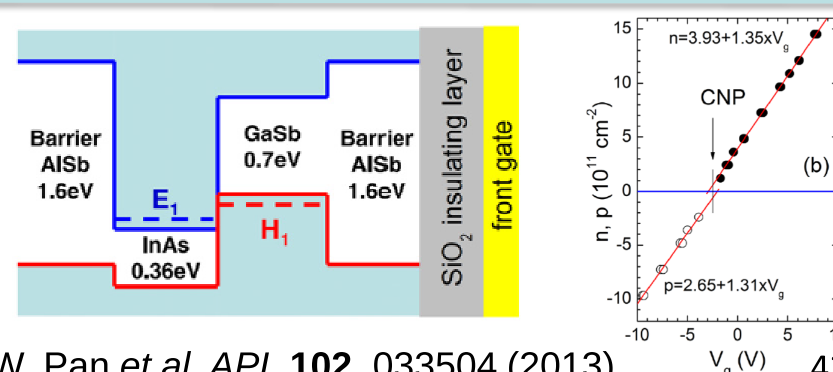
A. V. Muravjov, *et al.*, *APL* **96**, 042105 (2010)

- Graphene
  - FIR to MIR, room temperature
  - Dirac plasmons



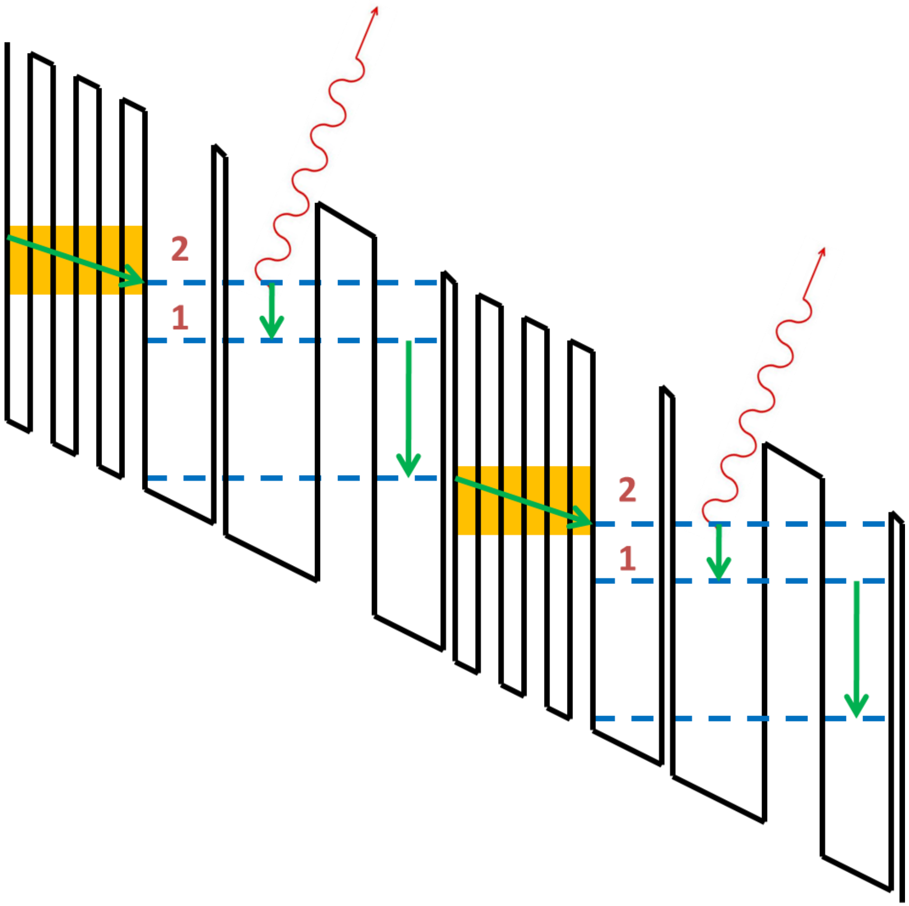
H. Yan *et al.*, *Nat. Nano.* **7**, 330 (2012)

- Type-II InAs/GaSb
  - 2DEG, 2DHG & CNP
  - p-n: $m_e = 0.03\ m_0$, $m_h = 0.37\ m_0$

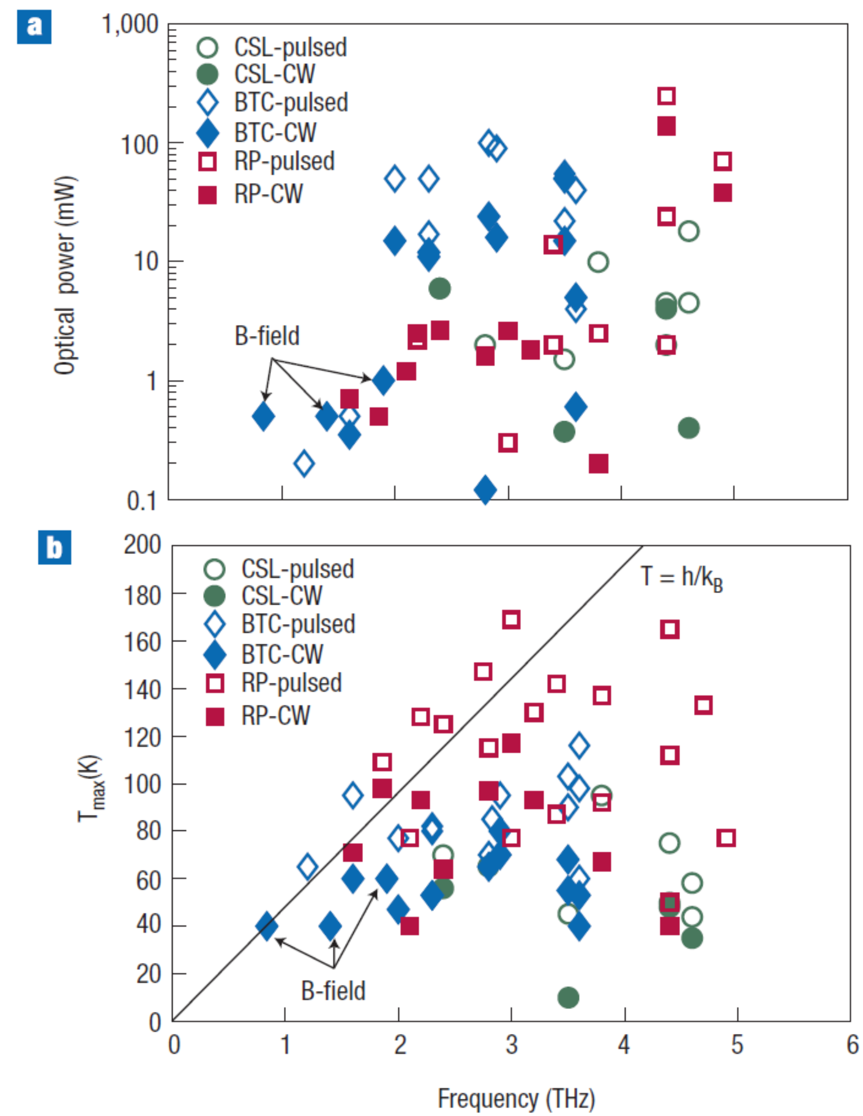


W. Pan *et al. APL* **102**, 033504 (2013)

THz Quantum Cascade Lasers

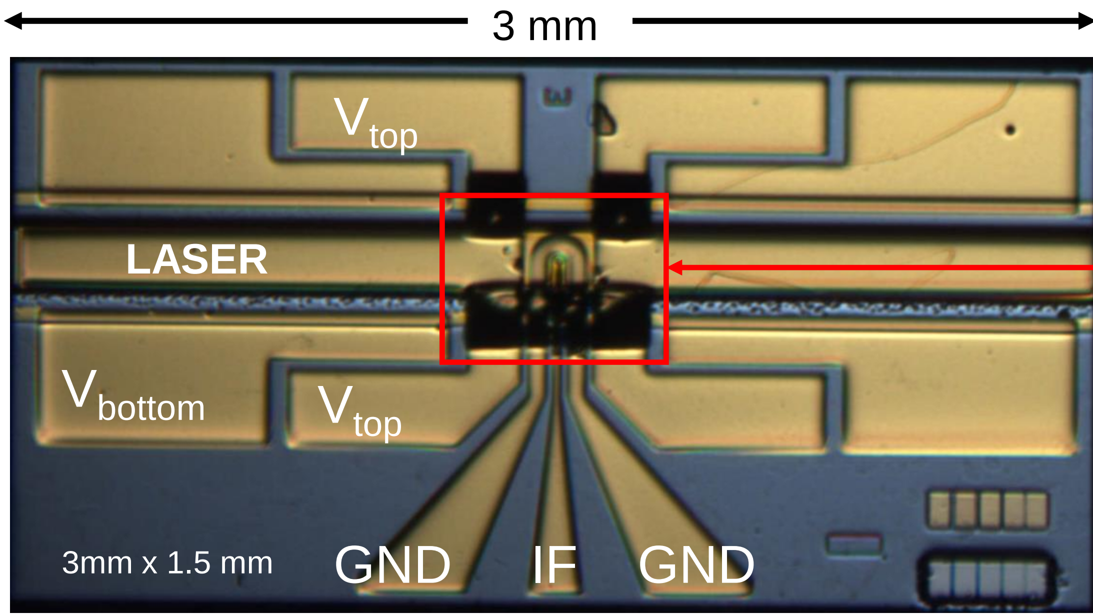


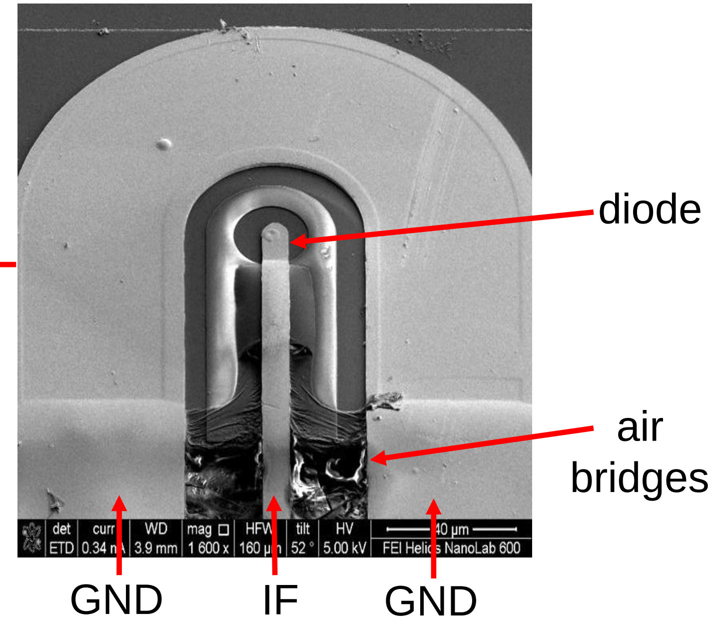
Unipolar semiconductor laser based on engineering of electronic states in conduction band

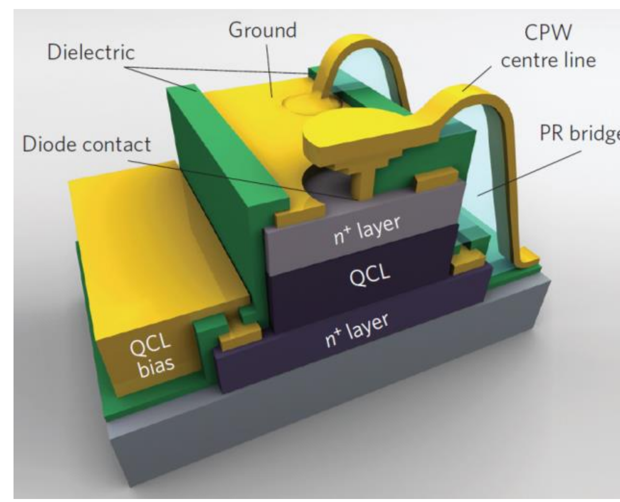


B. S. Williams, *Nat. Photonics* **1**, 517 (2007)

THz QCL Transceivers





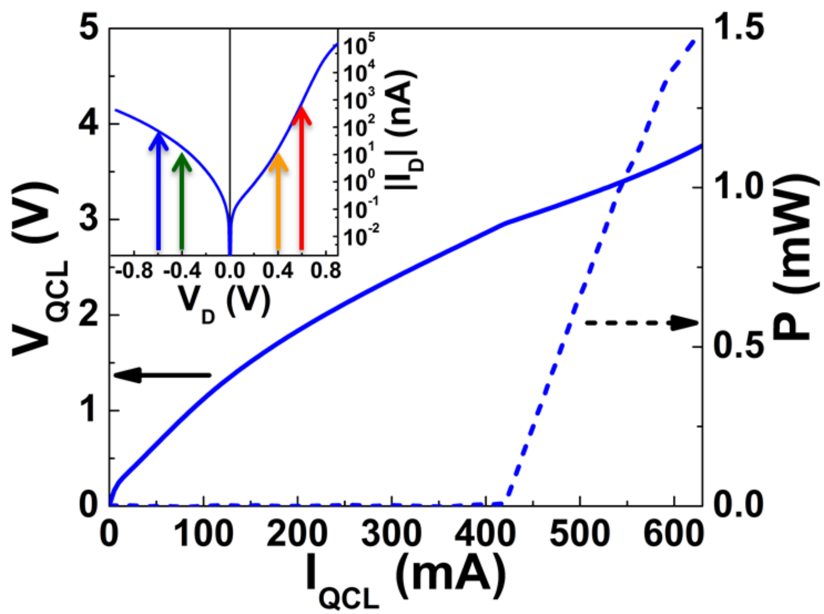


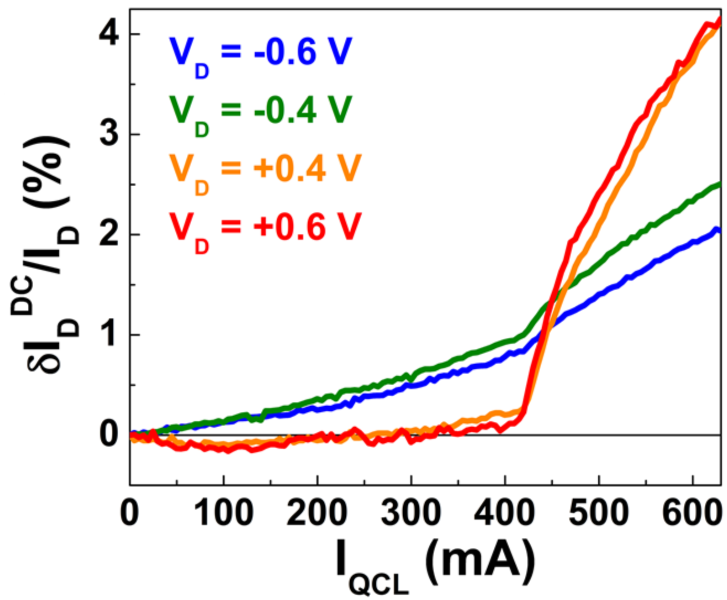
Schottky diode directly embedded into 2.8 THz QCL waveguide at cavity center

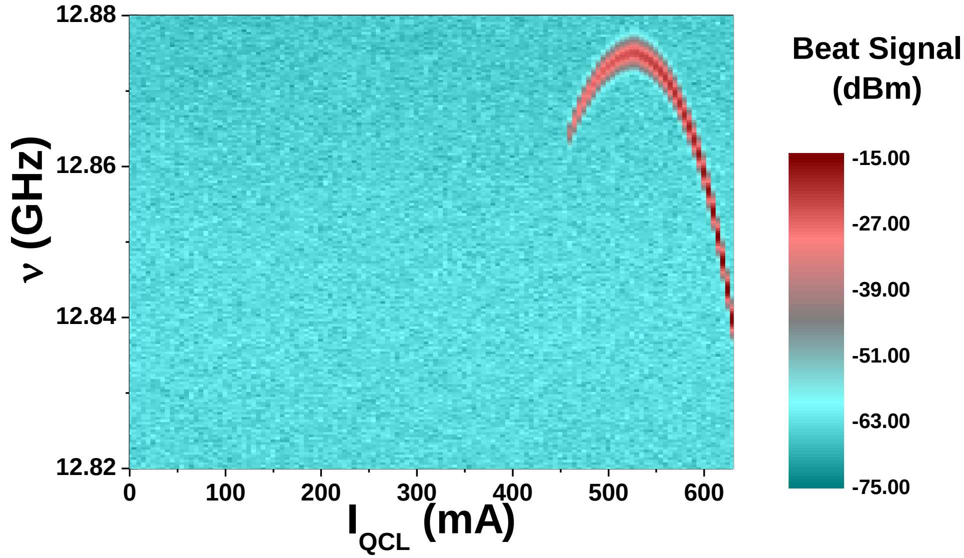
QCL functions as local oscillator (LO)

M. C. Wanke et. al., *Nat. Photonics* **4**, 565 (2010)

Rectified Diode Response





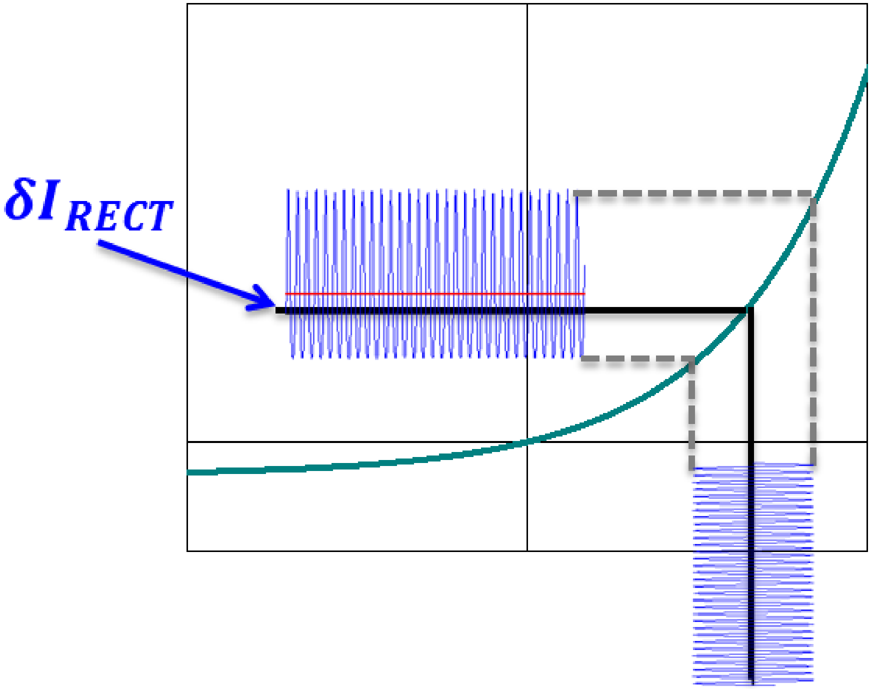


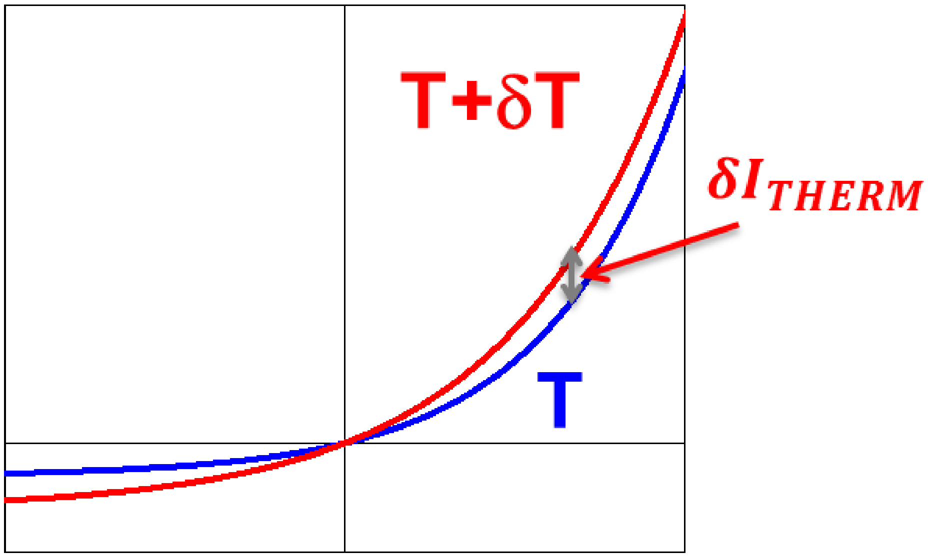
Rectified (DC) and beat (microwave) signals from QCL coupling to diode

G.C. Dyer *et al.*, *Opt. Express* **21**, 3996-4004 (2013)

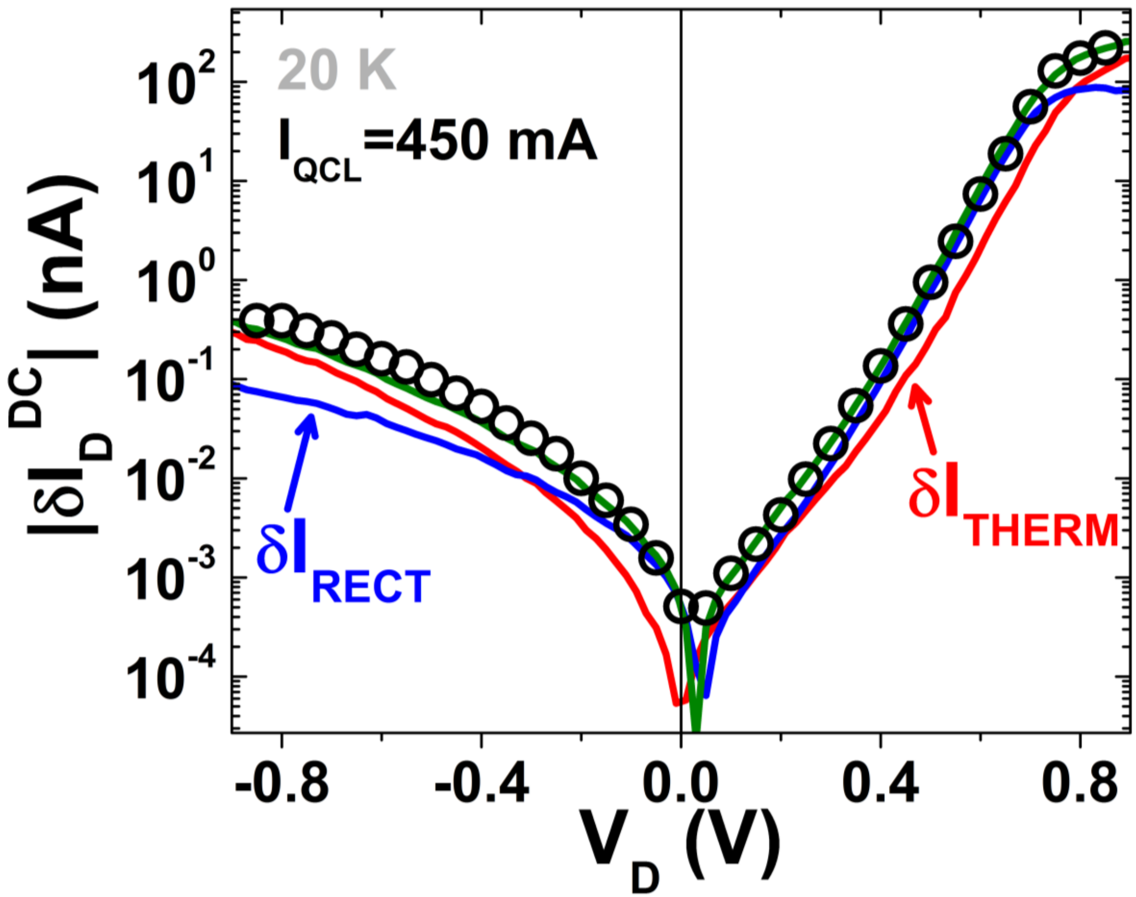
Ideal Diode Picture

$$I_D = I_0\left[exp\left(\frac{V_D}{k_B T}\right) - 1\right]$$





Model of Rectified Response



Circles: measured change in diode current with 'QCL on' vs. 'QCL off'

Derivatives: calculated from static diode I-V

δP_{QCL} calculated from static QCL I-V

Fit: Θ_T = 12.28 W/K & δV_{THz}^2 = 6.92 x 10^{-5} V^2

$$\delta I_D^{DC} = \frac{1}{4}\frac{\partial^2 I_D}{\partial V_D^2}\delta V_{THz}^2 + \frac{\partial I_D}{\partial T}\delta P_{QCL}\Theta_T$$

G.C. Dyer *et al.*, *Opt. Express* **21**, 3996-4004 (2013)

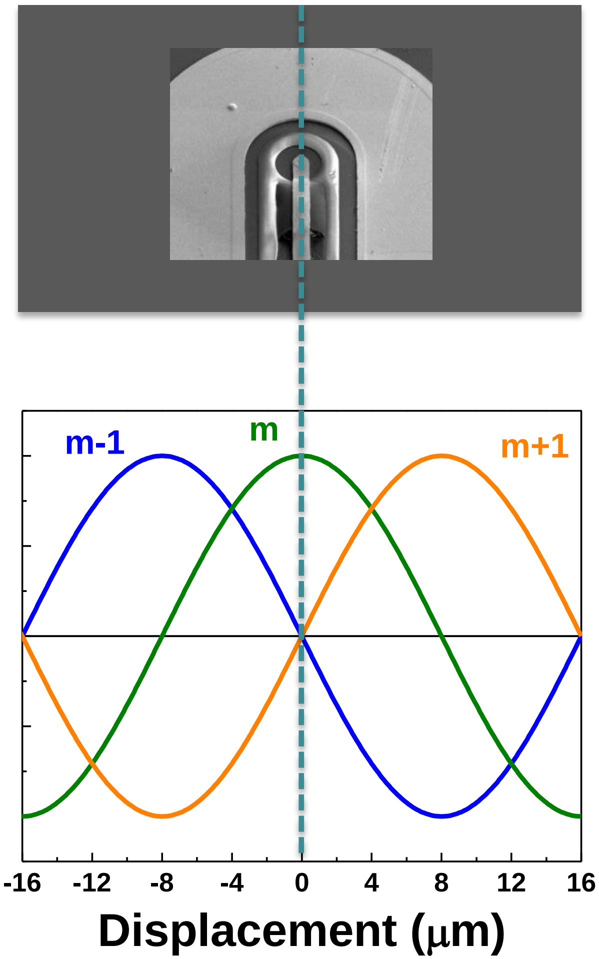
Relative Diode Positioning

Sandia National Laboratories

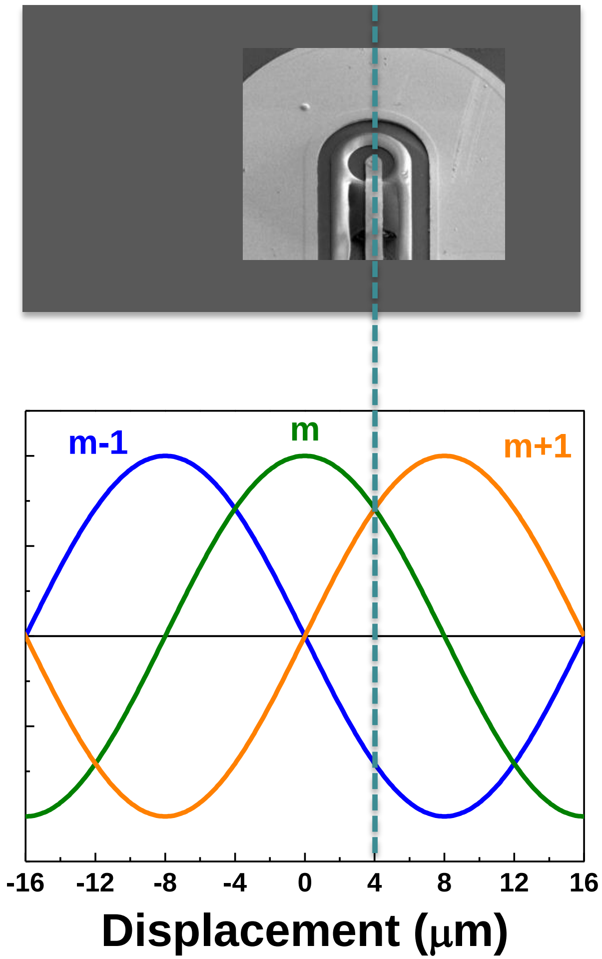
Diode location at center of QCL cavity

Fabry-Perot mode field distributions

diode at x = 0 μm (mid-cavity)



diode at x = +4 μm (λ /8 offset)



Lithographic Tuning

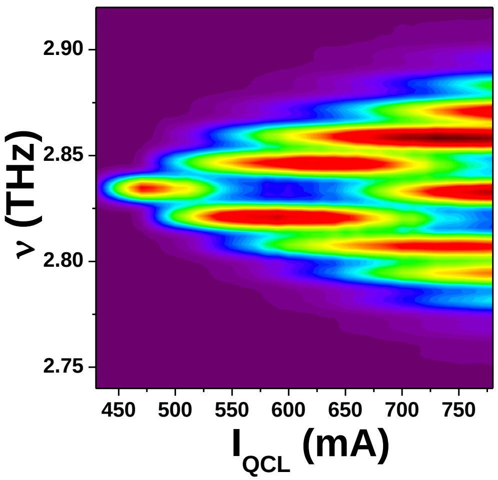
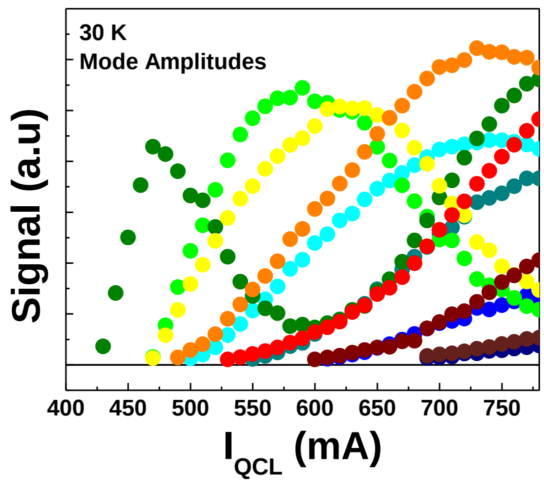
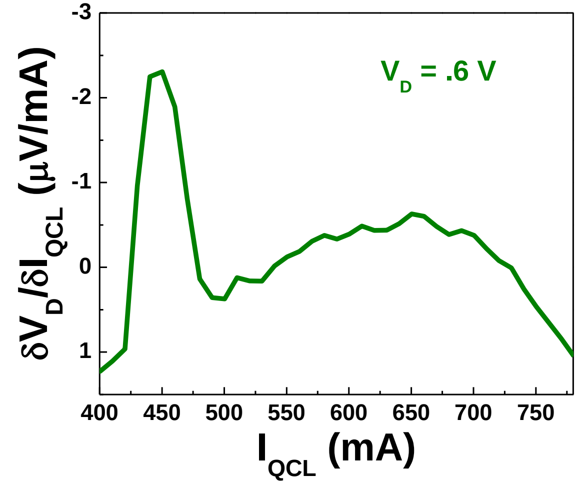
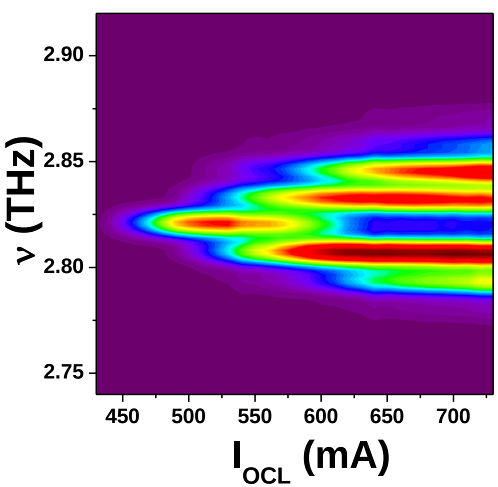
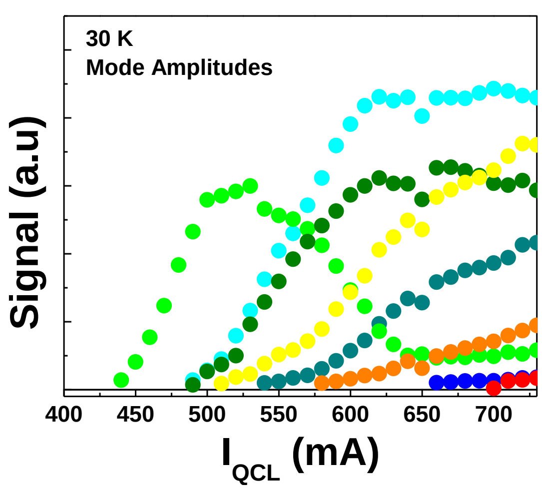
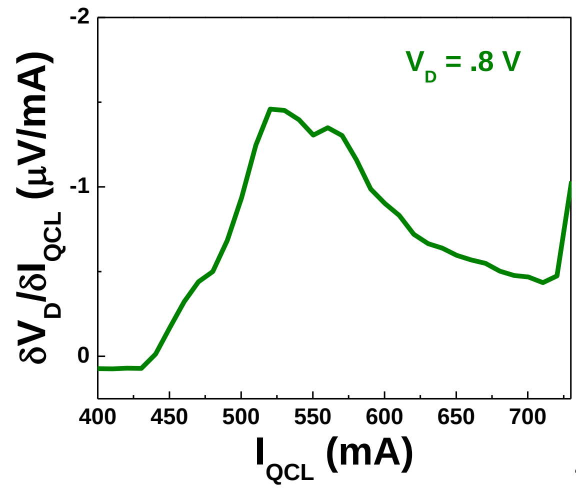
	QCL Emission	Mode Amplitudes	Rectified Signal
diode at x = 0 μm			
diode at x = +4 μm			

Image 1:

Image 2:

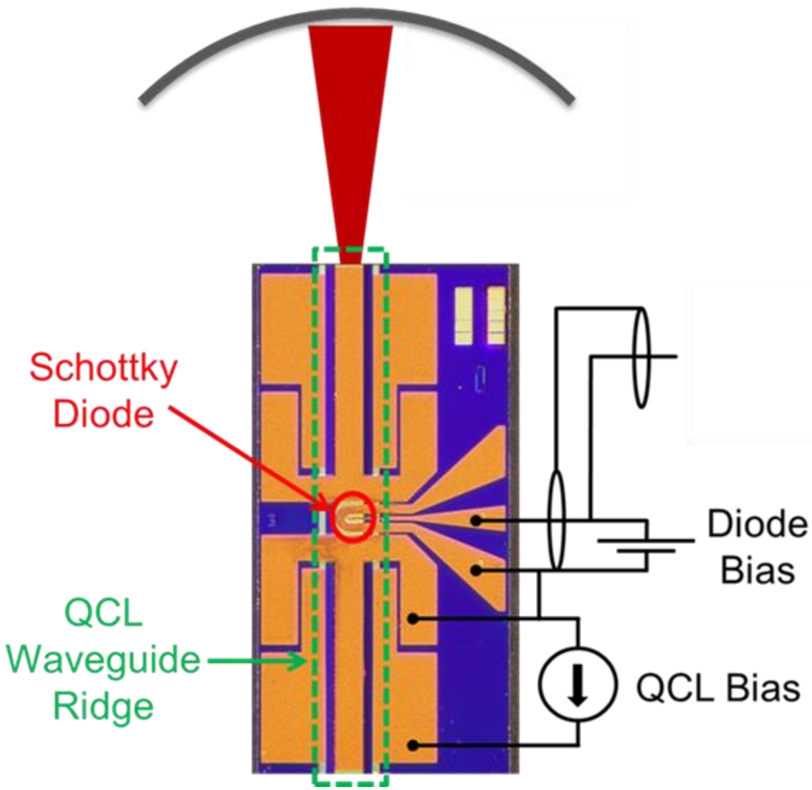
Image 3:

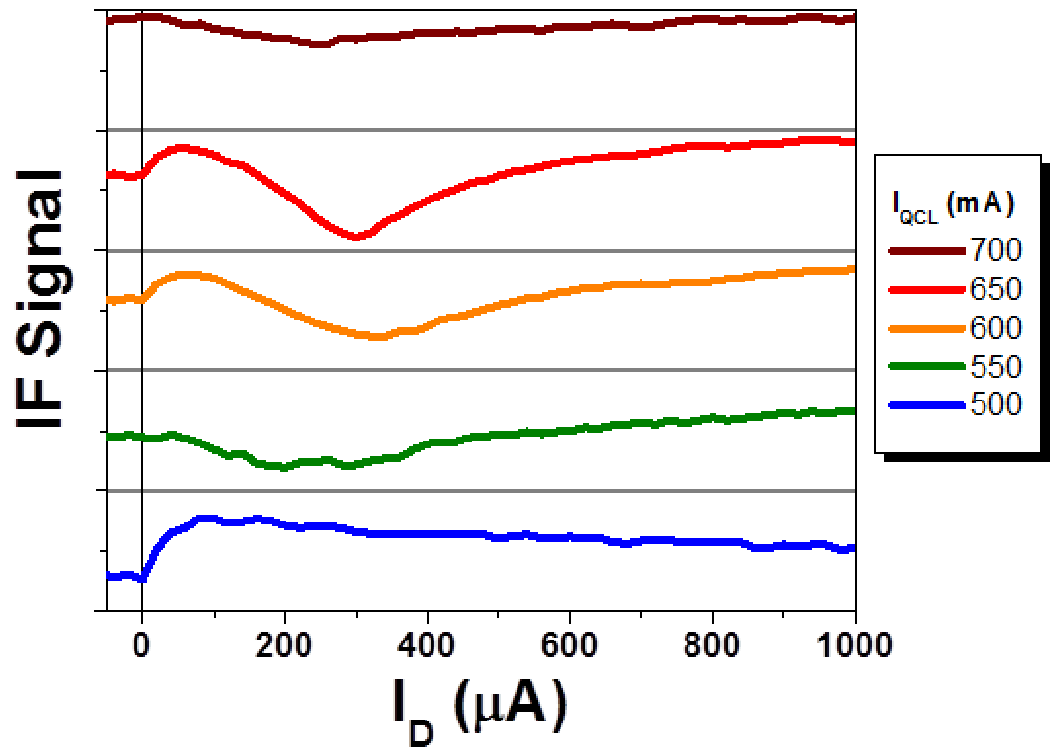
Image 4:

Image 5:

Image 6:

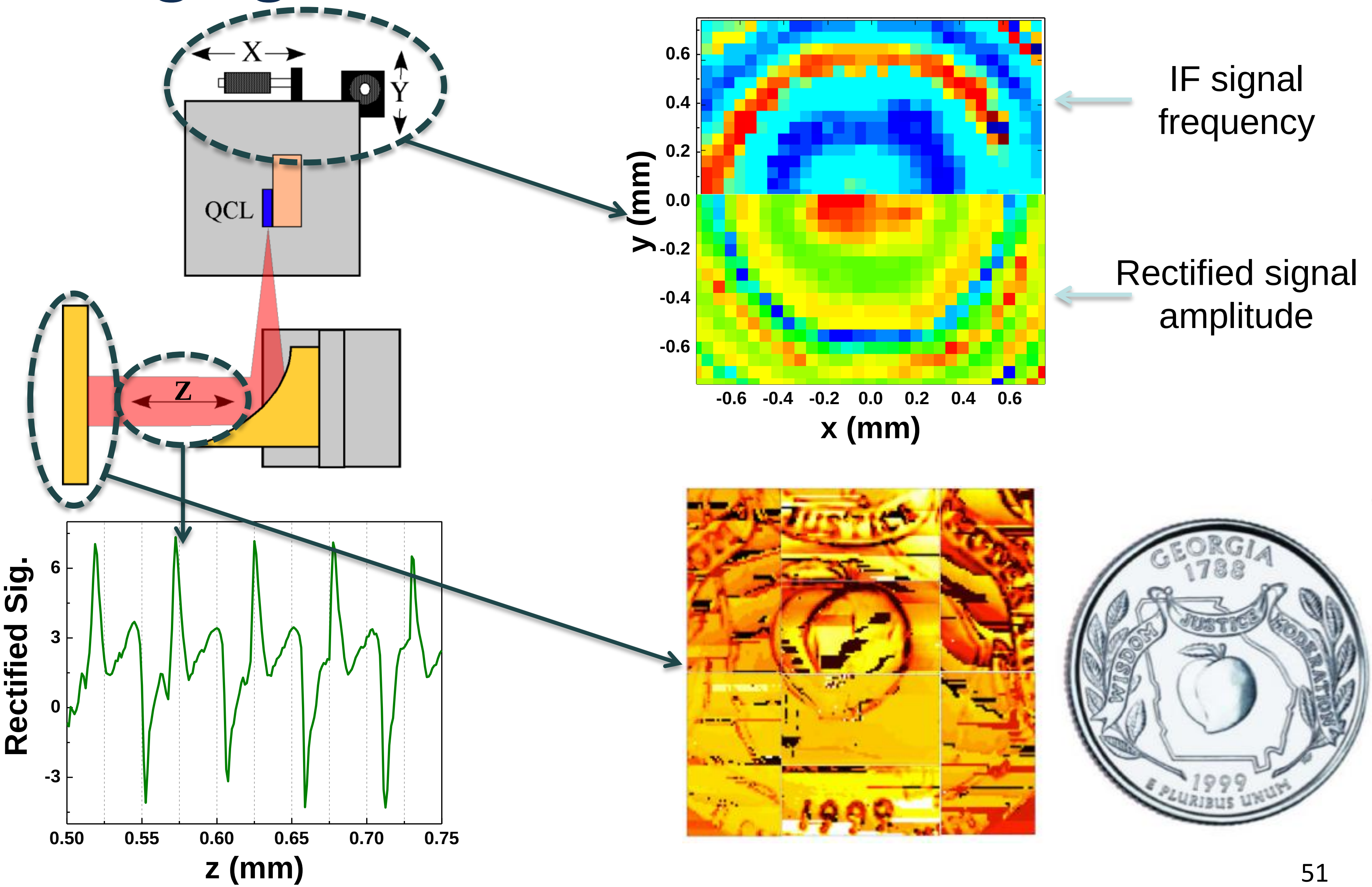
Diode-Laser Perturbation



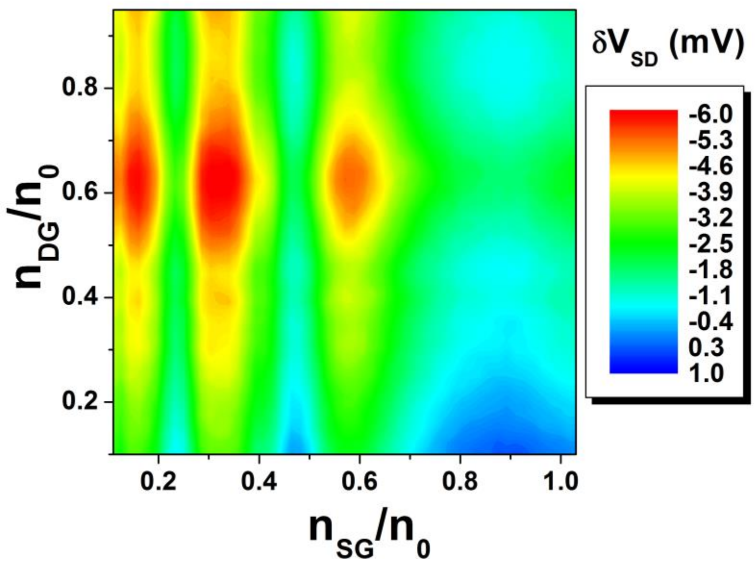


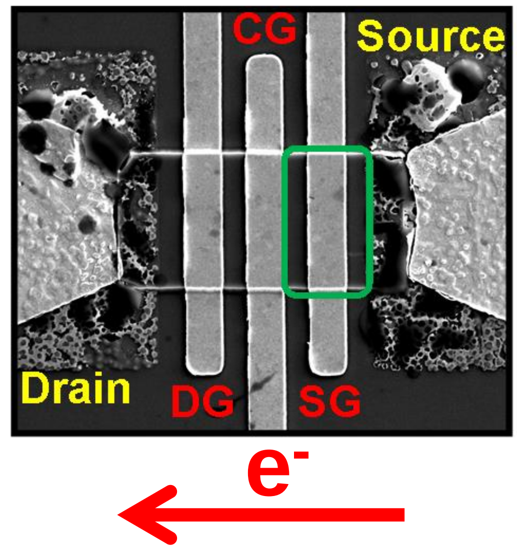
Non-monotonic change in beat signal tuning diode: perturbation of QCL modes

Imaging via Feedback



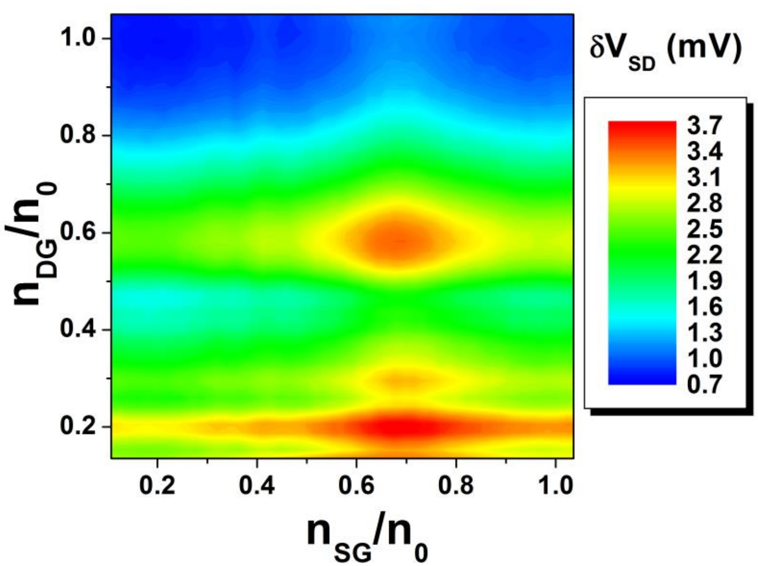
Source-Drain Bias Cavity Selection

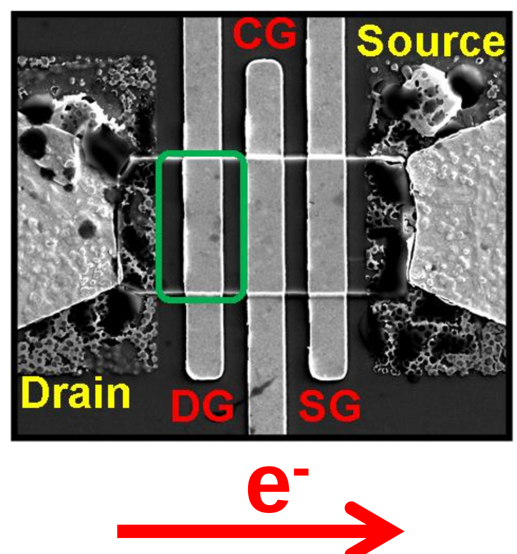




370 GHz

***I* = +500 nA**





***I* = -500 nA**

G. C. Dyer et. al., *APL* **100**, 083506 (2012)

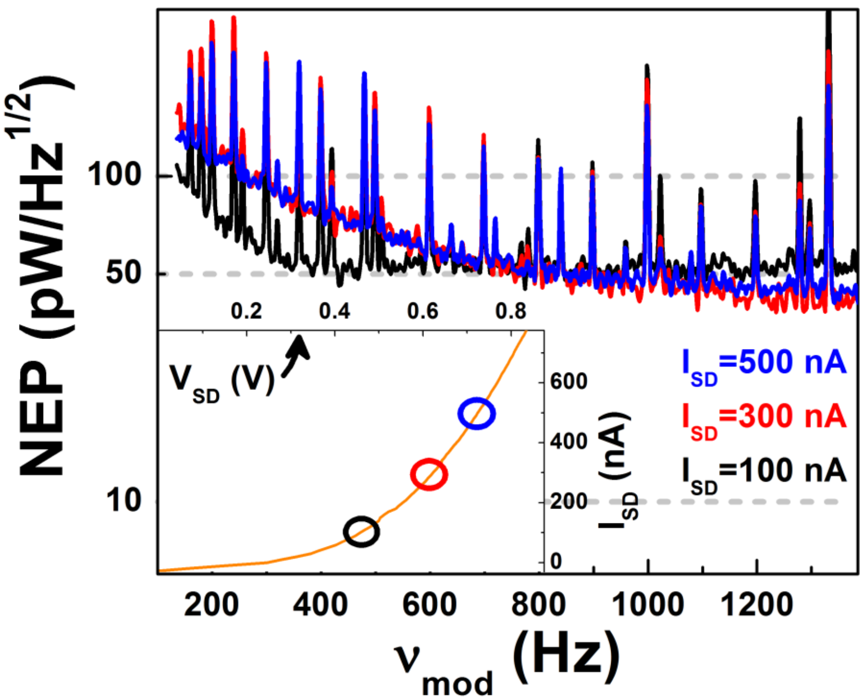
Bolometric Detection FOMs

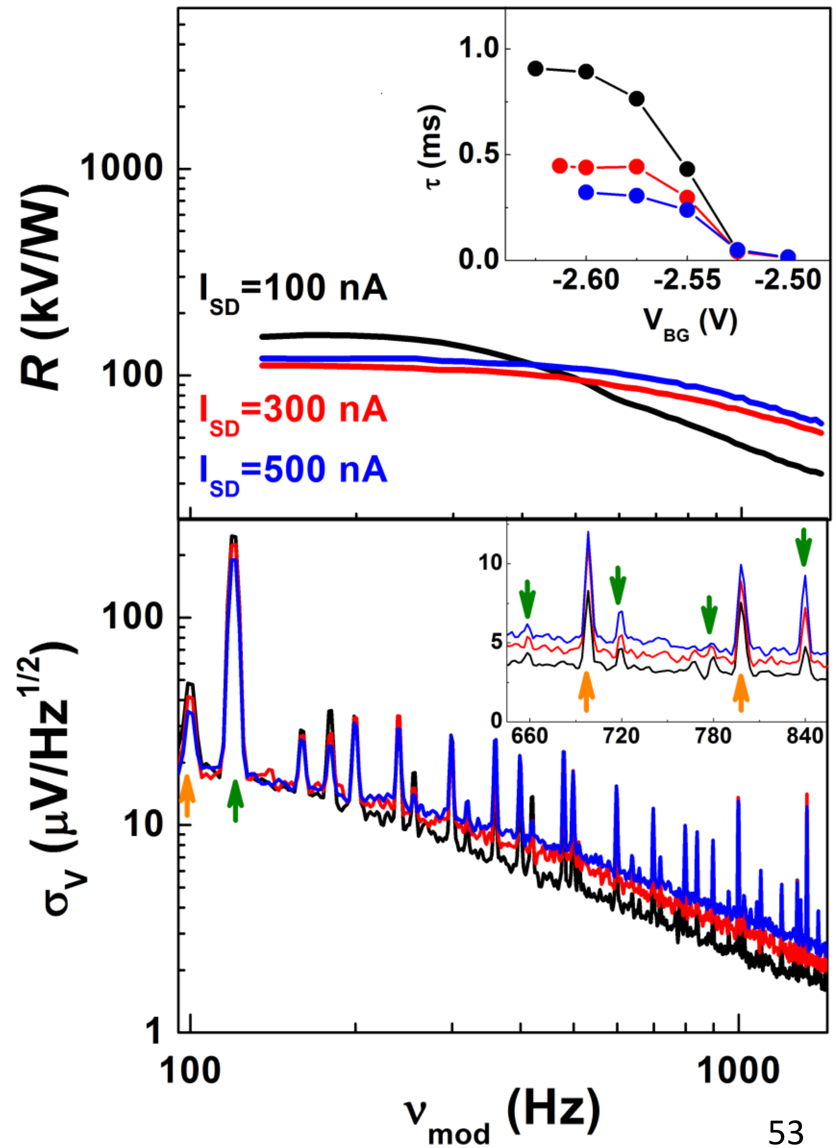
Sandia National Laboratories

11K Operation, 243 GHz

***R* > 100 kV/W**

***NEP* < 50 pW/Hz$^{1/2}$**

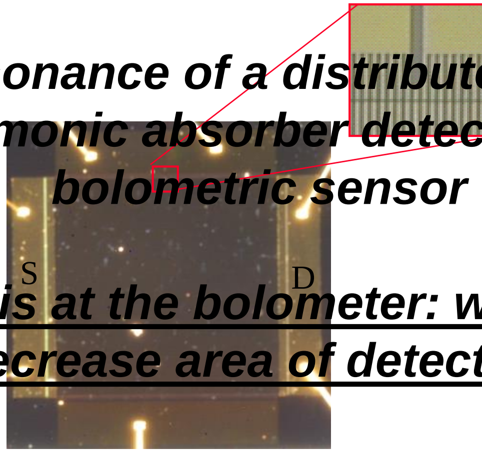




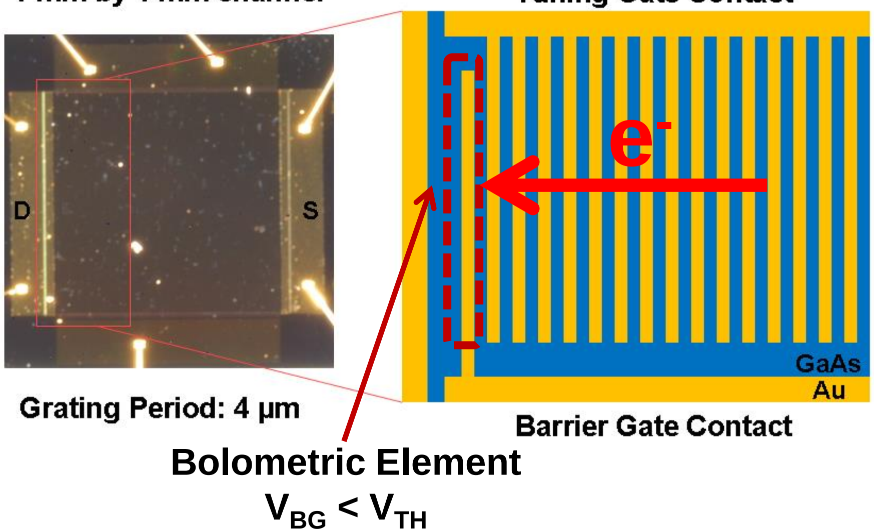
G. C. Dyer et. al., *APL* **100**, 083506 (2012)

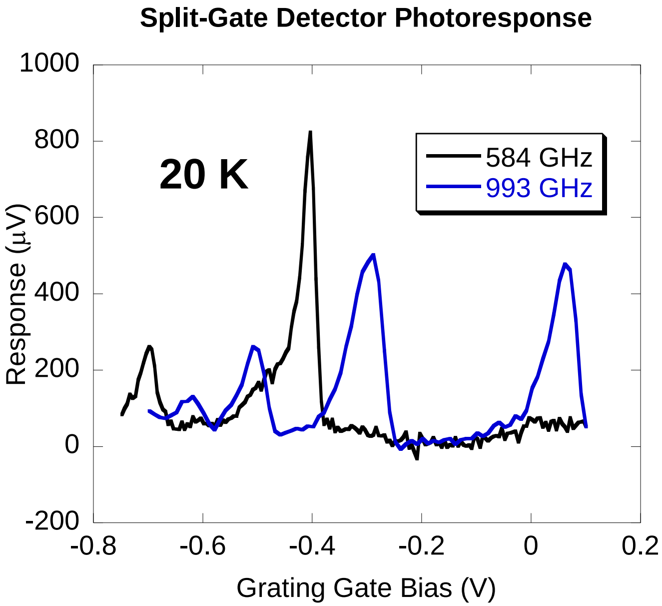
Resonant Terahertz Response

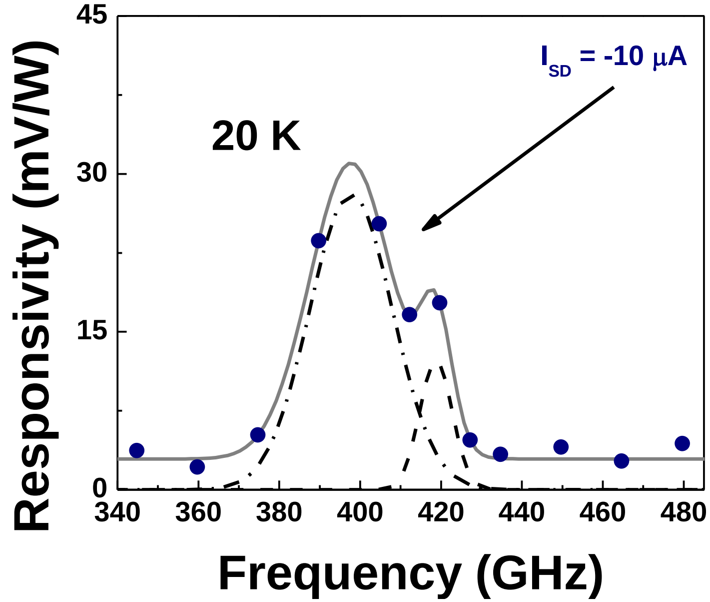
Resonance of a distributed 2D plasmonic absorber detected by bolometric sensor



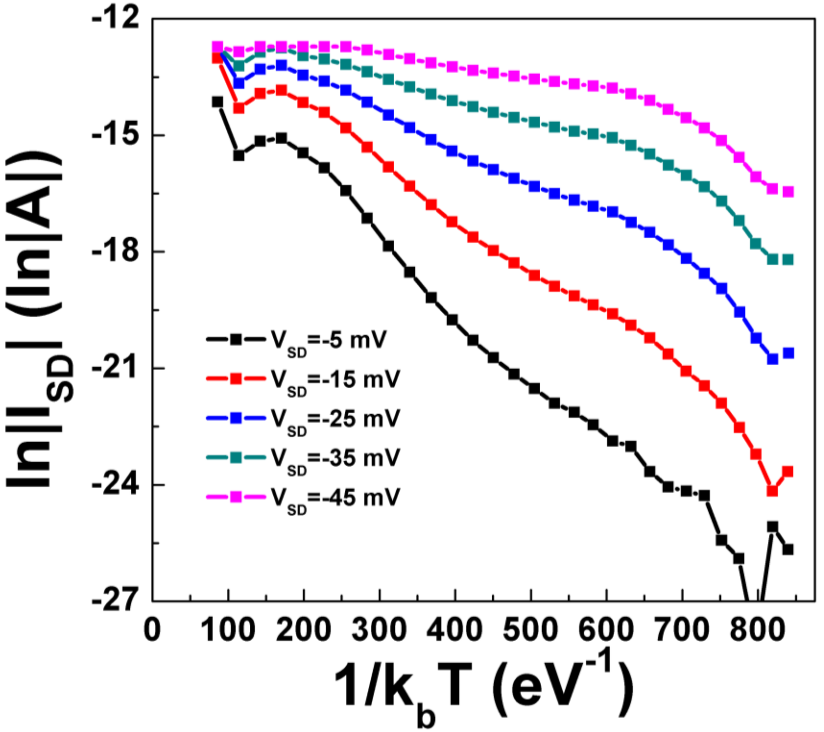
Action is at the bolometer: what if we decrease area of detector?

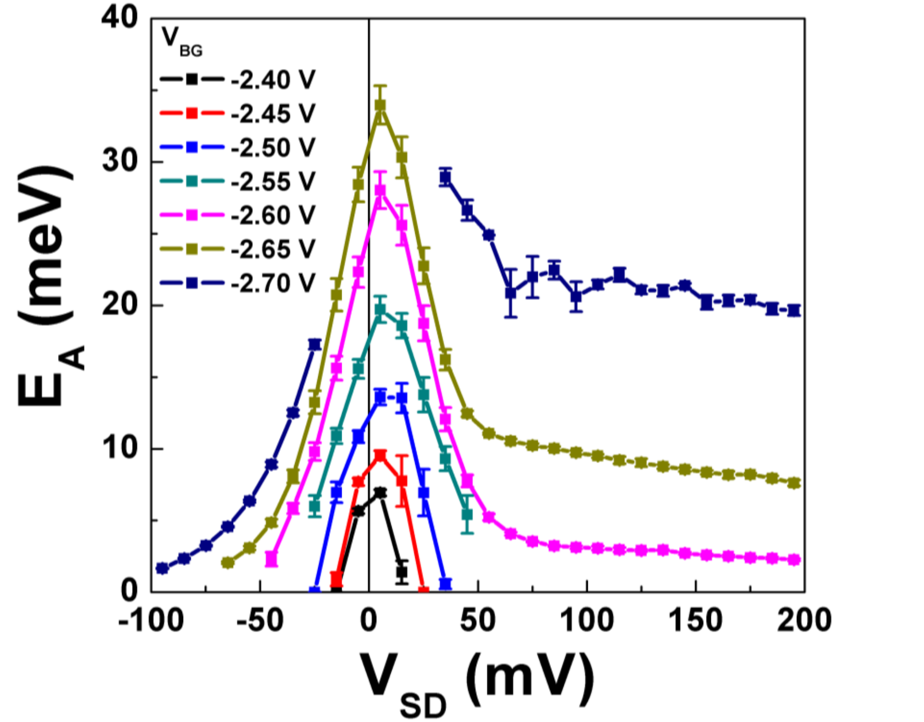






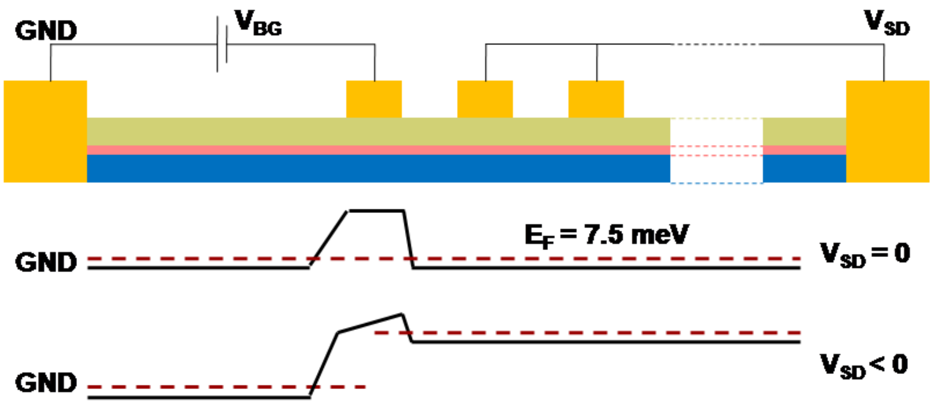
Activation Energy

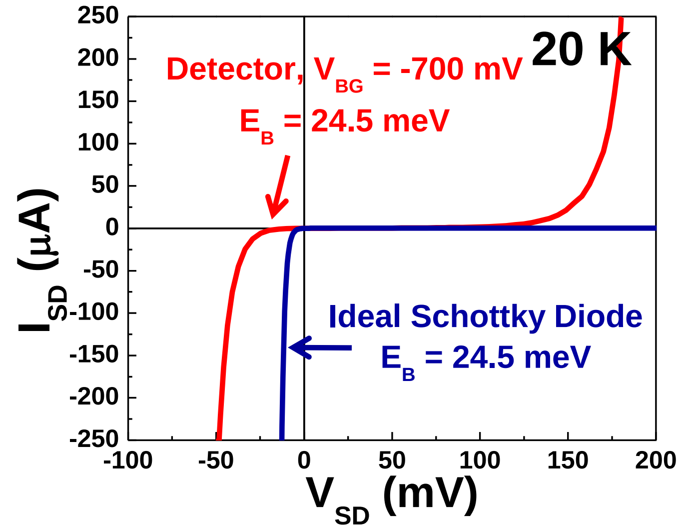




- Double quantum well material, V_{TH} ~ -2.40 V
- Left: Arrhenius plots V_{BG} = -2.6 V, fits from 200-600 eV^{-1}
- Right: activation energy as a function of bias

Barrier Lowering ($V_{SD} < 0$)





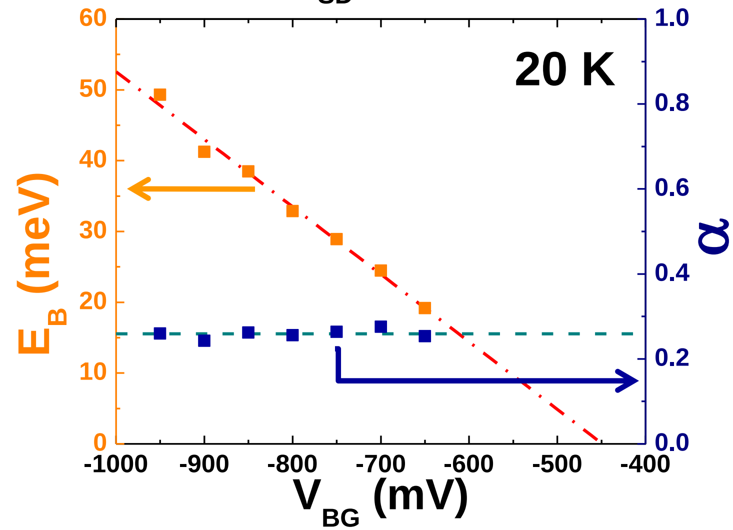
Non-Degenerate Limit, Negative Bias

IF $E_B - \mu + e\alpha V_{SD} \gg k_B T$:

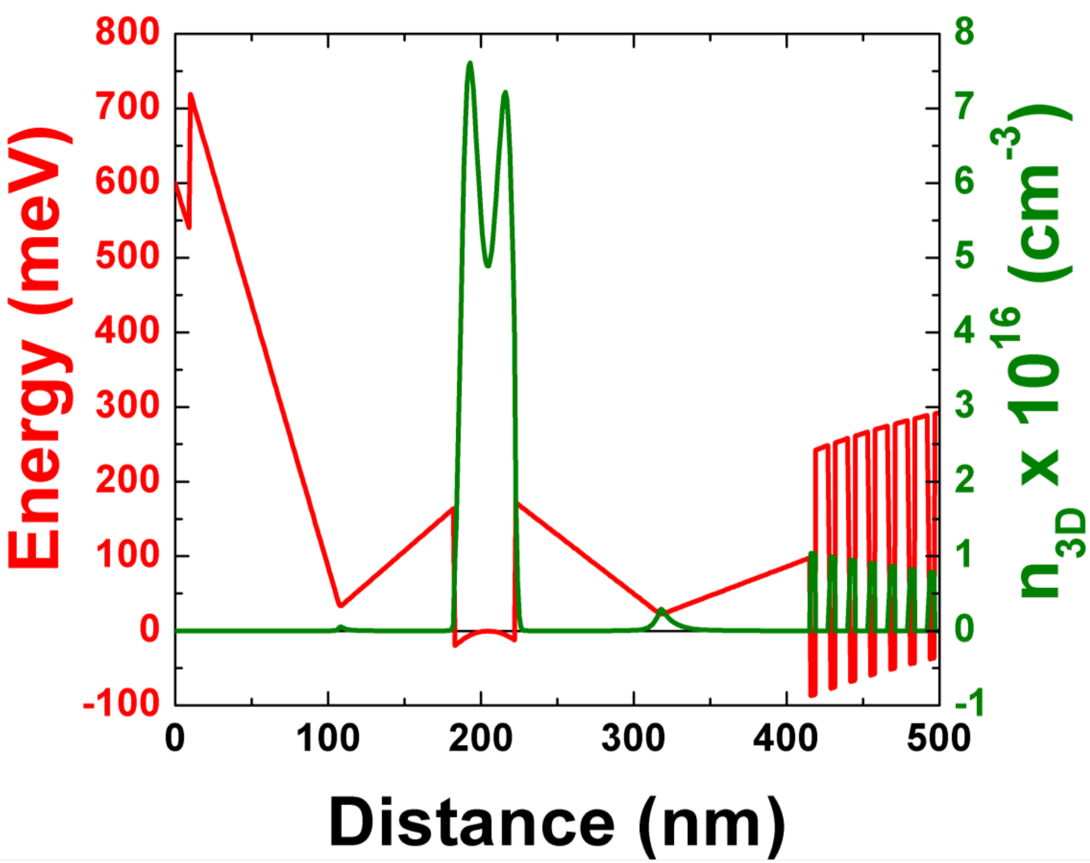
$$J_{2D} \propto -e^{\frac{-E_B}{k_B T}} e^{\frac{-e\alpha V_{SD}}{k_B T}}$$

Barrier Height E_B

Barrier Lowering Parameter α



Schrodinger Poisson Model

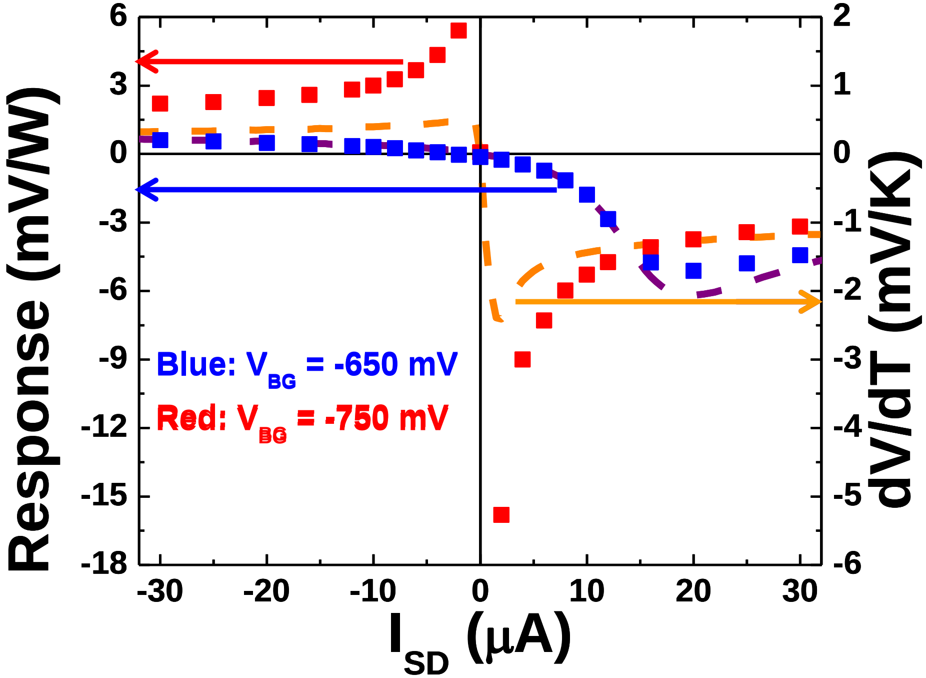


- Via Greg Snider's 1D Schrodinger-Poisson solver
- Carrier density in backside delta doping and superlattice
- Potential for parallel channel, 'lever arm'
- From lateral barrier activation model:

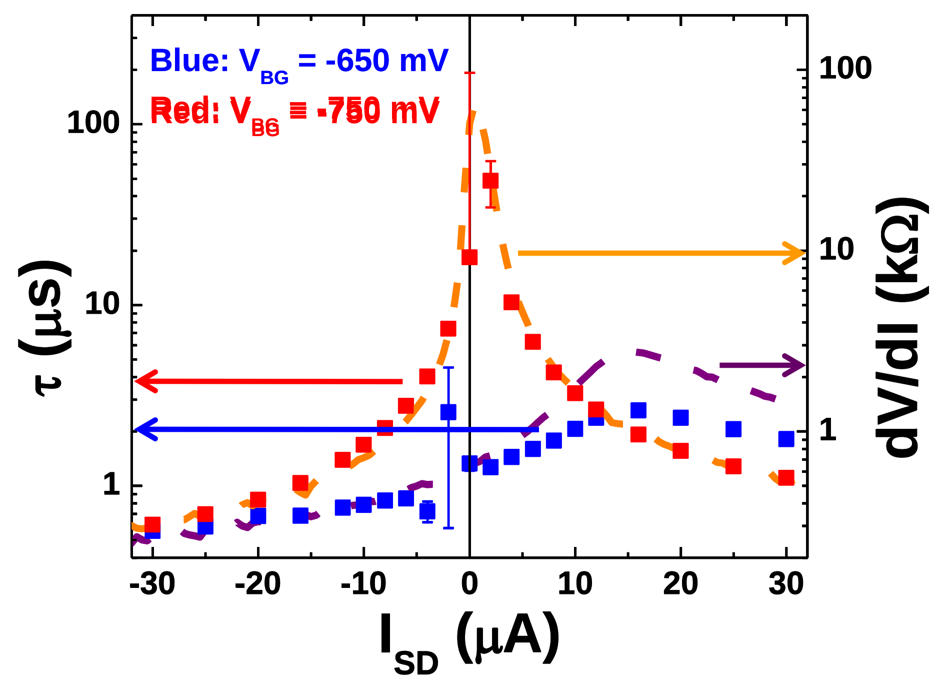
$$\left[\frac{\partial V_{SD}}{\partial T}\right]_{\max} \approx \mp 0.08625 \frac{E_A}{\alpha_{\pm} k_B T}$$

Hot Electron Bolometric Response

40 K, 420 GHz



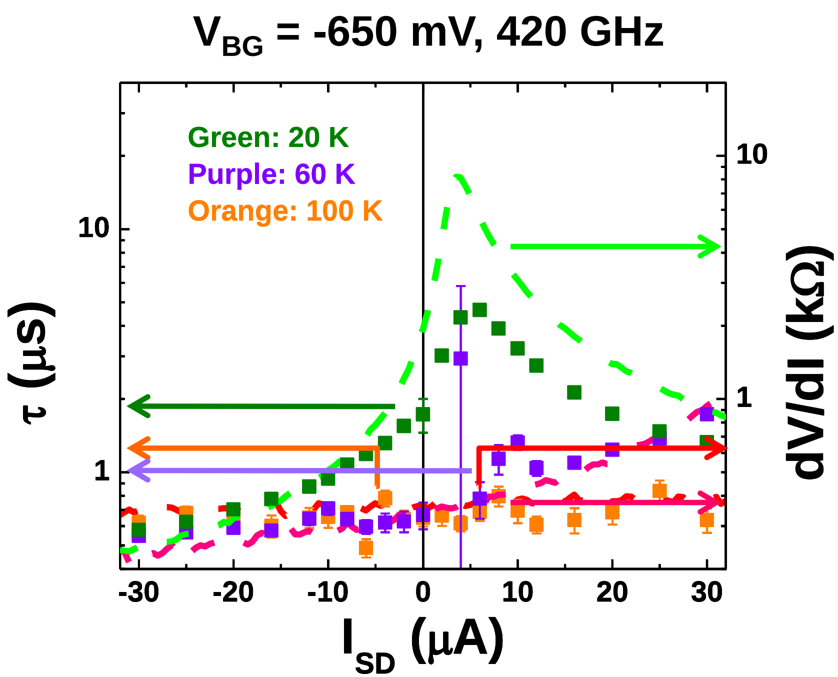
40 K, 420 GHz

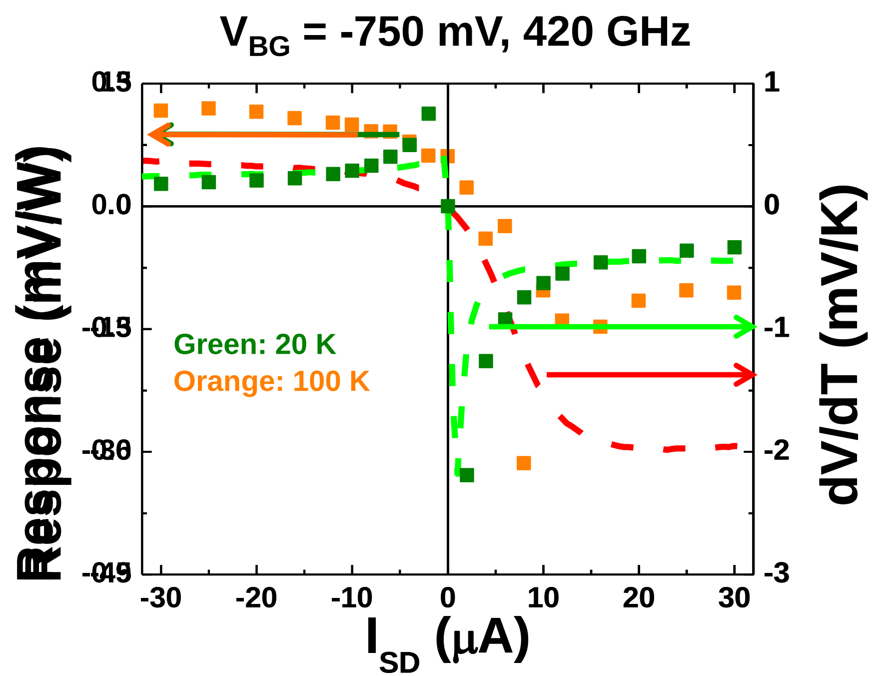


$$\text{Response} \propto \frac{\partial V}{\partial T}$$

$$\tau = R_d C = \frac{\partial V}{\partial I} C$$

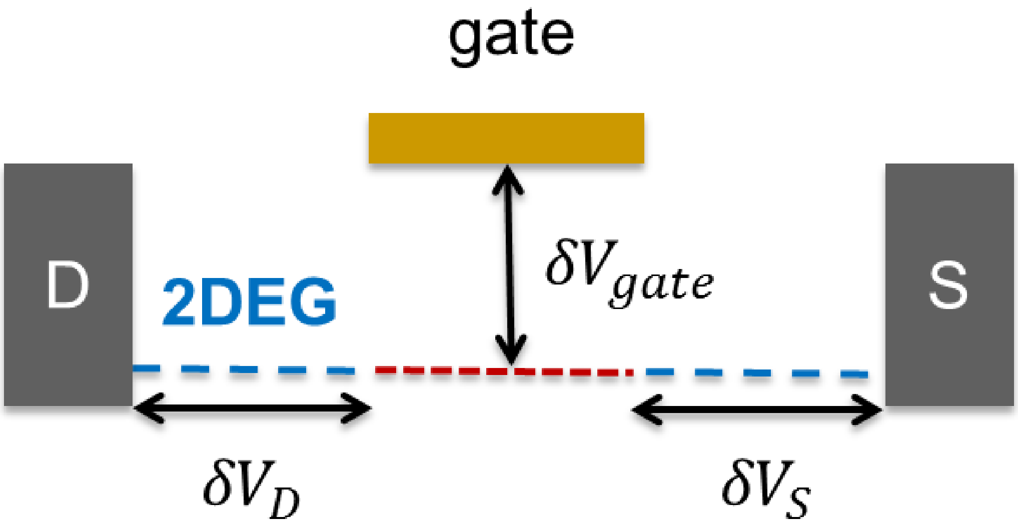
Temperature Dependence

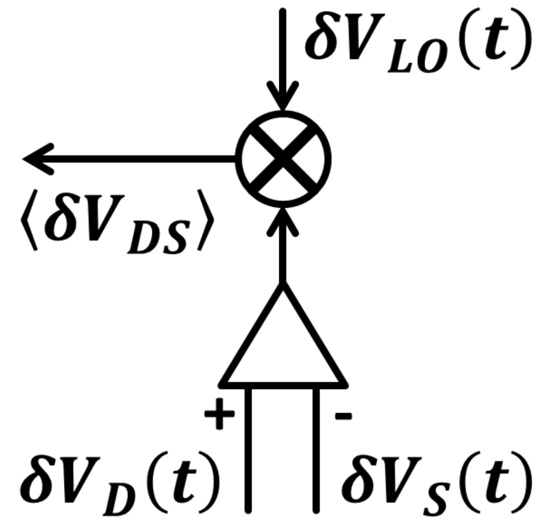




- Response described by “RC” over broad range of T
- Response must be scaled to agree with *dV/dT*
- Scale factor: approx. .07 W/K at 20 K, 3 W/K at 100 K

Plasmonic Homodyne Mixing





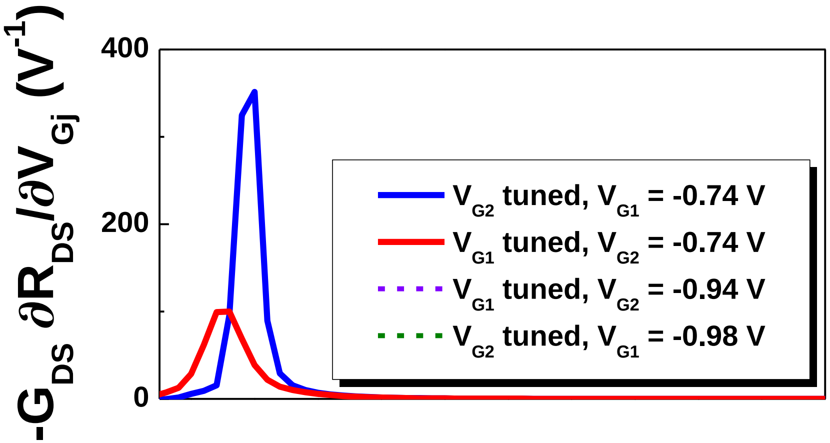
$$\langle \delta V_{DS} \rangle = \left\langle \left[\frac{\partial R_{chan}}{\partial V_{gate}} \delta V_{gate} e^{-i(\omega t + \emptyset)} \right] [\delta V_D - \delta V_S] e^{-i\omega t} G_{chan} \right\rangle$$

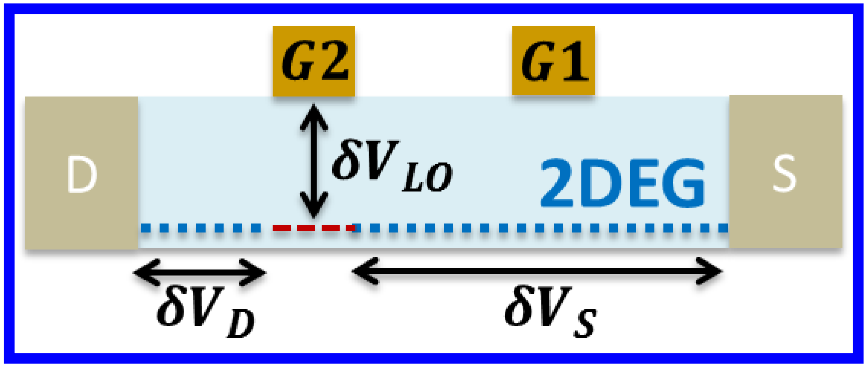
$$= \frac{1}{2} \left[G_{chan} \frac{\partial R_{chan}}{\partial V_{gate}} \right] \delta V_{gate} [\delta V_D - \delta V_S] cos[\emptyset]$$

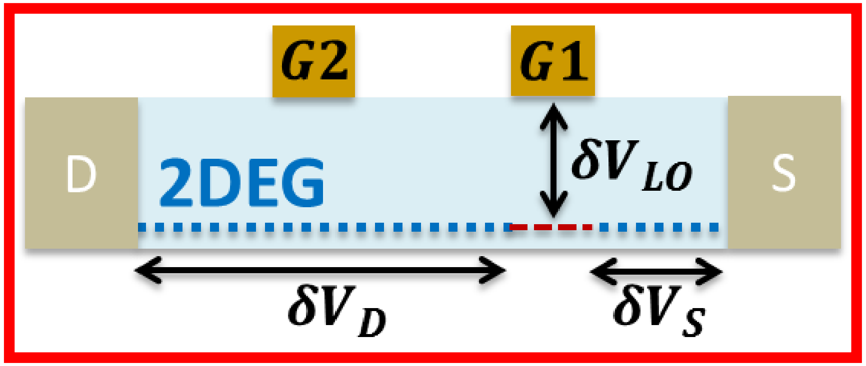
$\emptyset$ is relative phase between gate & channel THz potentials

A. Lisauskas *et al. J. Appl. Phys*. **105**, 114511 (2009).

Homodyne Mixing Photovoltage

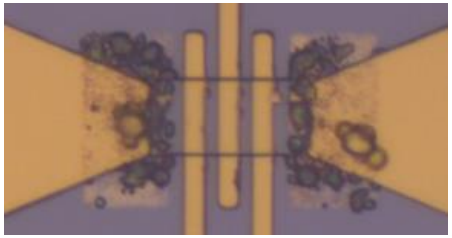


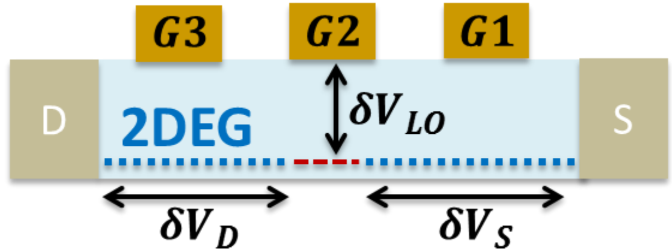




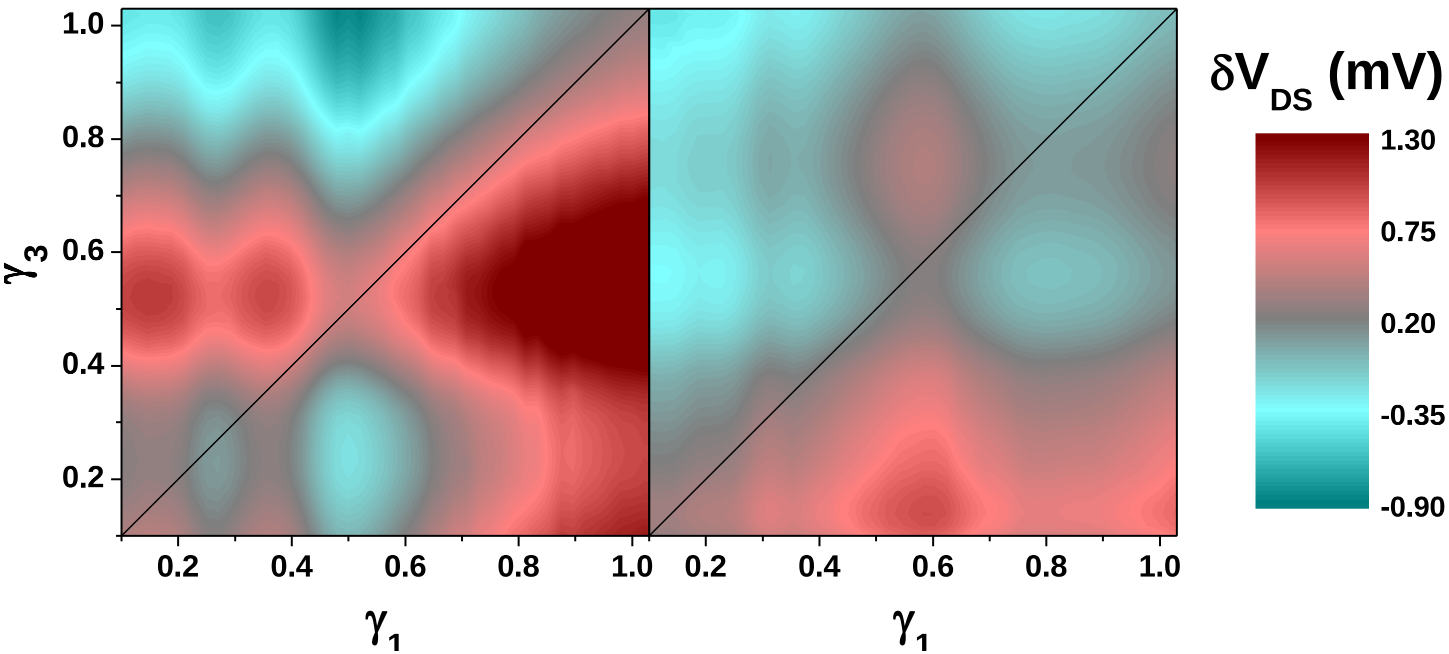
G.C. Dyer *et al.*, manuscript in preparation

Two Path Plasmonic Mixing





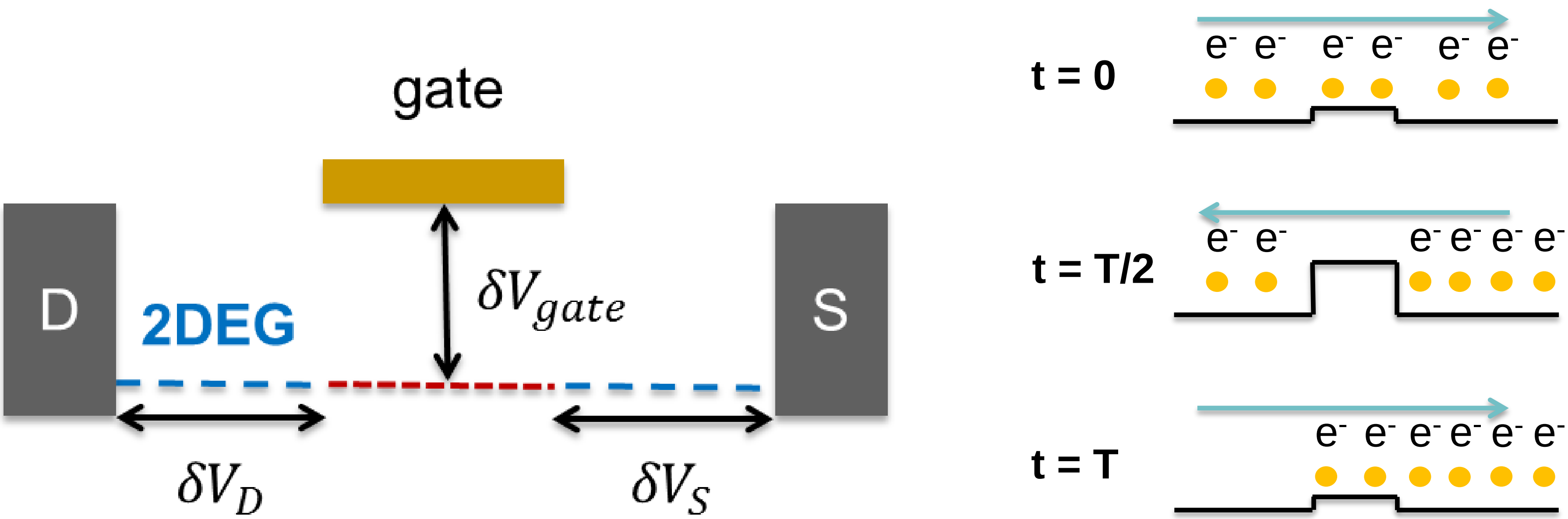
327 GHz **370 GHz**



Physical path length ***L*** fixed, electrical length ***qL*** is tuned

G.C. Dyer *et al.*, manuscript in preparation

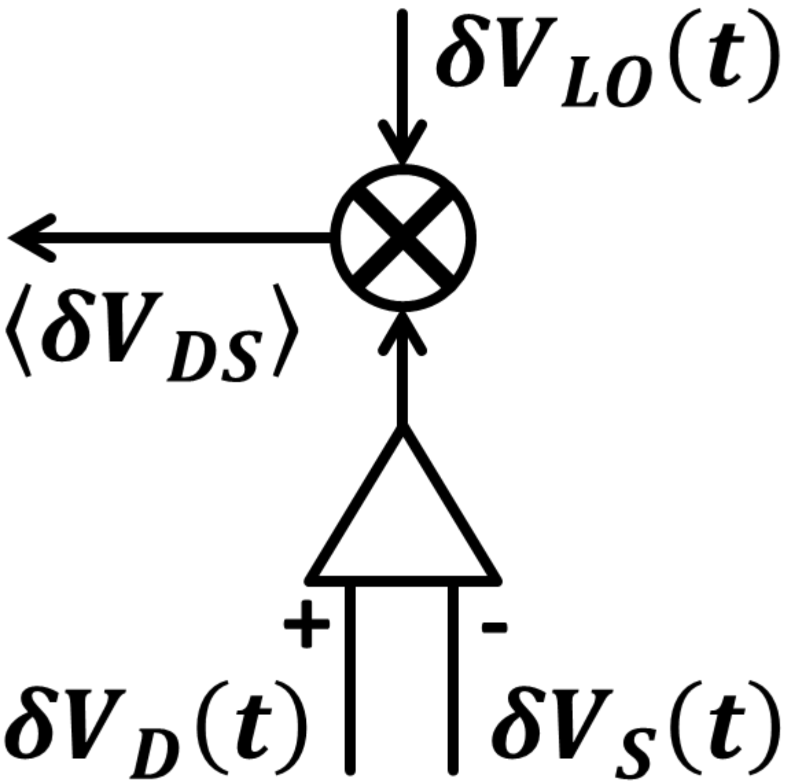
Plasmonic Homodyne Mixing



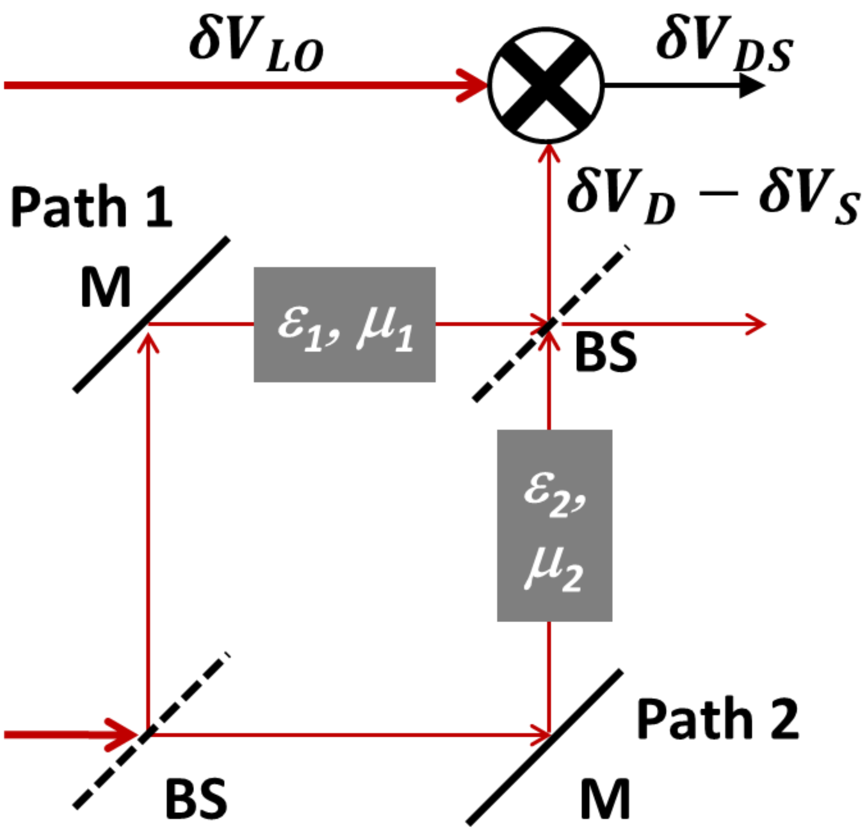
THz field coupled to channel (blue) drives current across depleted region (red) which is rectified by gate THz field

A. Lisauskas *et al. J. Appl. Phys*. **105**, 114511 (2009).

Mach-Zehnder Analogue



Equivalent Optical Interferometer



G.C. Dyer *et al.*, manuscript in preparation

Inductance Comparison

Treat gated 2DEG like a single wire loop

Inductance per unit length along x-direction

$$L_{kinetic} = \frac{m^*}{e^2 n_{2D} W} \sim 50\ \mu_0$$

$$L_{geometric} = \frac{d}{W}\mu_0 \sim 0.05\ \mu_0$$

Magnetic flux per unit length through x-z plane

$$\Phi_m \sim \frac{\mu_0 I d}{W} = I L_{geometric}$$

Growth Sheet

EPI-A GROWTH SHEET — EA0741

SAMPLE ID: EA0741 **OBJECTIVE:** High Mobility Structure
DATE: 02-May-01 **CUSTOMER:** Lilly,M
GROWER: Reno, J. **MATERIAL:** GaAs, AlGaAs

Structure

#	Material	Thickness	Dopant	Density	Temp.	SL	Comment
1	GaAs	10.0 nm	undoped		635 °C		Cap
2	AlGaAs	98.0 nm	undoped		635 °C		24.1%
3	delta-dope	0.0 nm	Si (n)	1.00E+12	635 °C		
4	AlGaAs	75.0 nm	undoped		635 °C		Upper Setback 24.1%
5	GaAs	30.0 nm	undoped		635 °C		QW
6	AlGaAs	95.0 nm	undoped		635 °C		Lower Setback24.1%
7	delta-dope	0.0 nm	Si (n)	1.00E+12	635 °C		
8	AlGaAs	98.0 nm	undoped		635 °C		24.1%
9	GaAs	3.0 nm	undoped		635 °C	[x300	Smoothing & EtchStop SL
10	AlGaAs	10.0 nm	undoped		635 °C	]	54.8%
11	GaAs	100.0 nm	undoped		635 °C		Buffer

Substrate Information

Ingot: G079K3400
Slice:
Material: GaAs
Orientation: (100)
Thickness: 625 µm
Diameter: 3"
Type: undoped
Vendor: AXT

Source Information

Source	Temp °C	Flux	G.R. ML/s	Rheed	UFG	Comment
Al7	1155.0		0.242	Yes	Yes	
As2_Va	175.0		1.760	Yes	Yes	
As2C	650.0		0.000	No	Yes	
As2X	390.0		0.000	No	Yes	
Ga3	1158.0		0.762	Yes	Yes	GaAs, 24.1% AlGaAs
Ga9	1090.0		0.199	Yes	Yes	54.8% AlGaAs
Rotate	-15.0		0.000	No	Yes	
Rotate	-5.0		0.000	No	Yes	Buffer
Si	1212.0		0.000	No	Yes	

Notes and Comments:

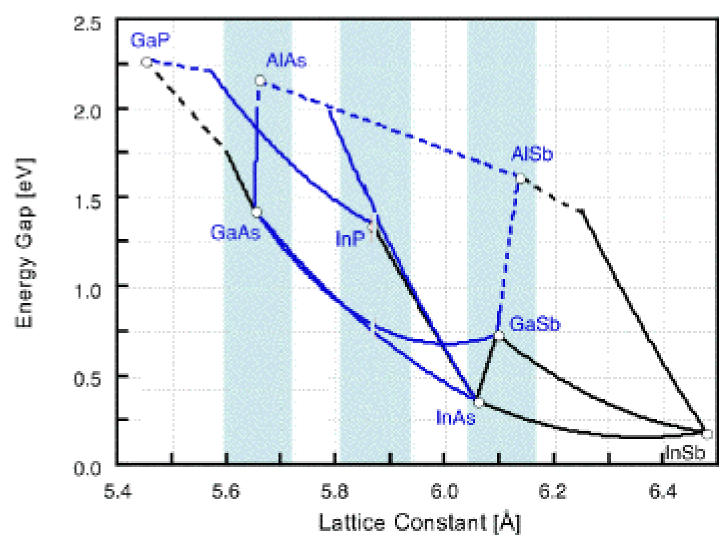
Duplicate of EA0739 but grown with lower As flux.

Characterization Results:

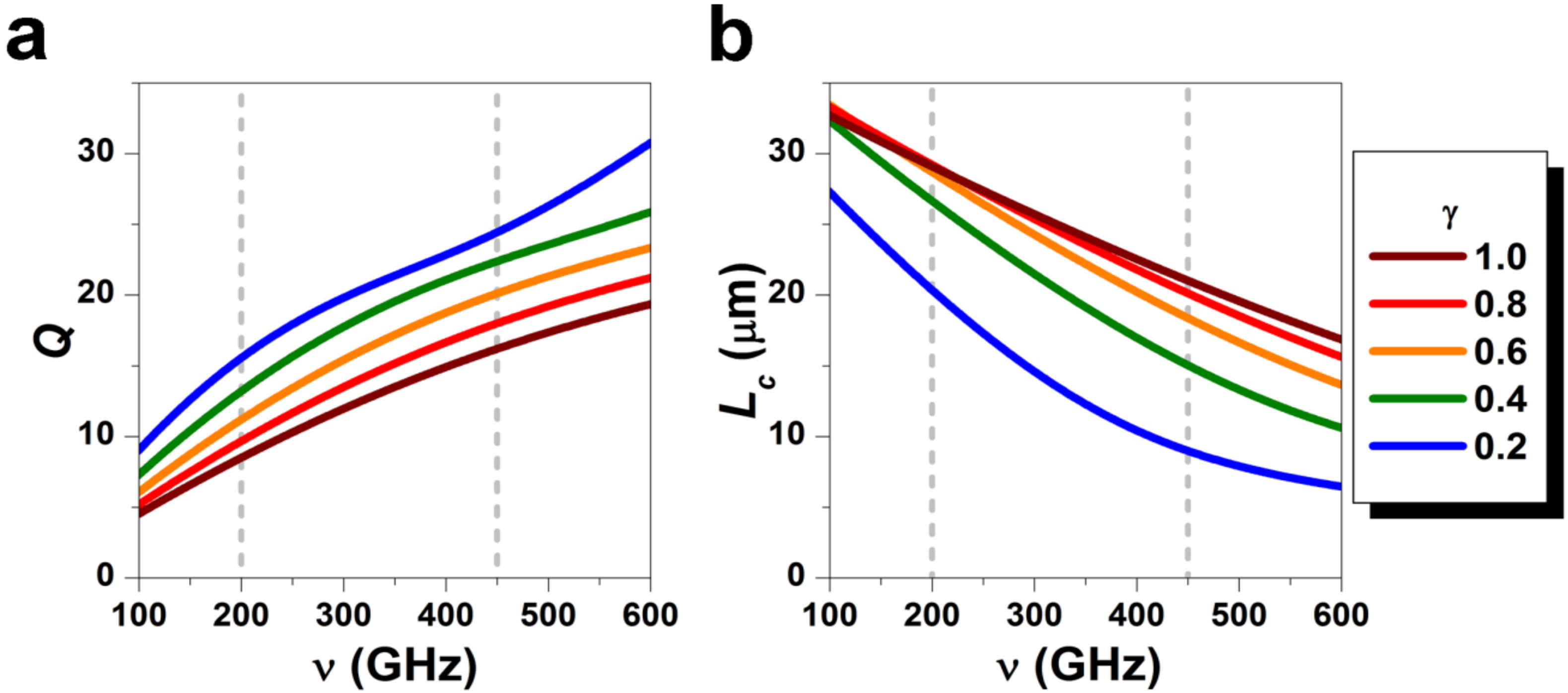
1

GaAs / $Al_xGa_{1-x}As$

x = .24



Q & Coherence Length

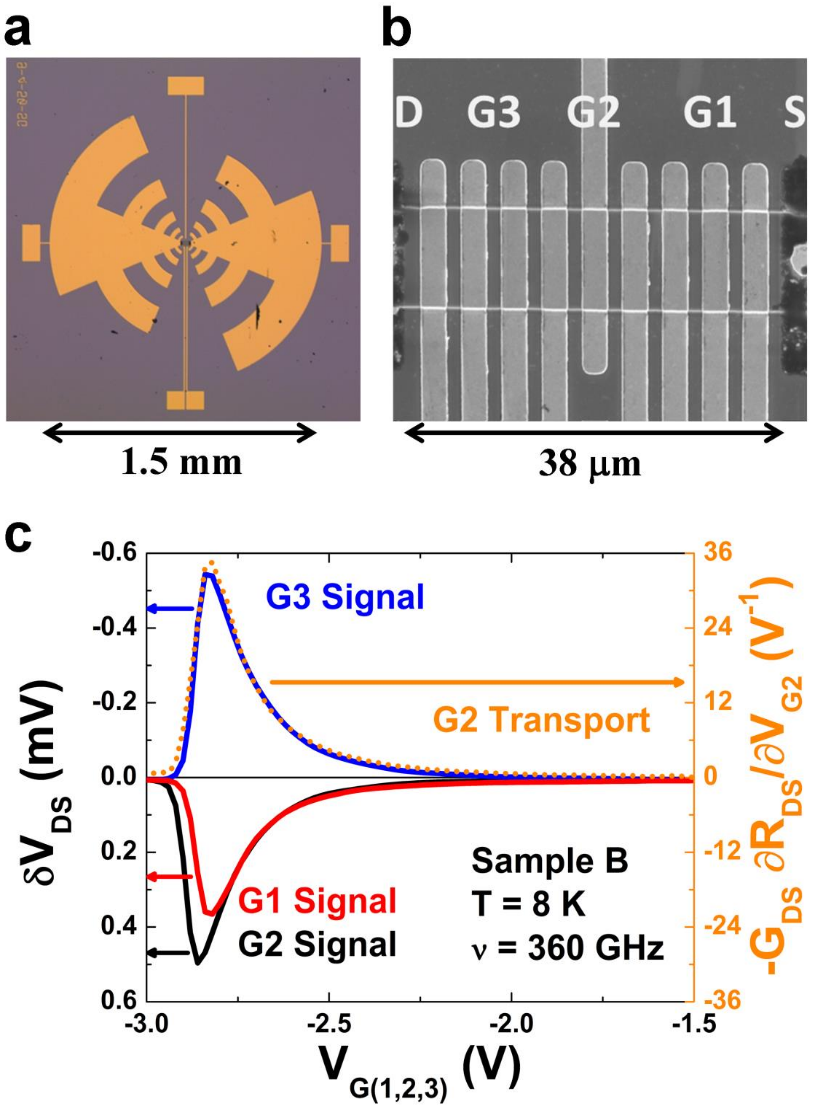


$$Q = \frac{\beta}{2\alpha}$$

$$L_c = \frac{1}{\alpha}$$

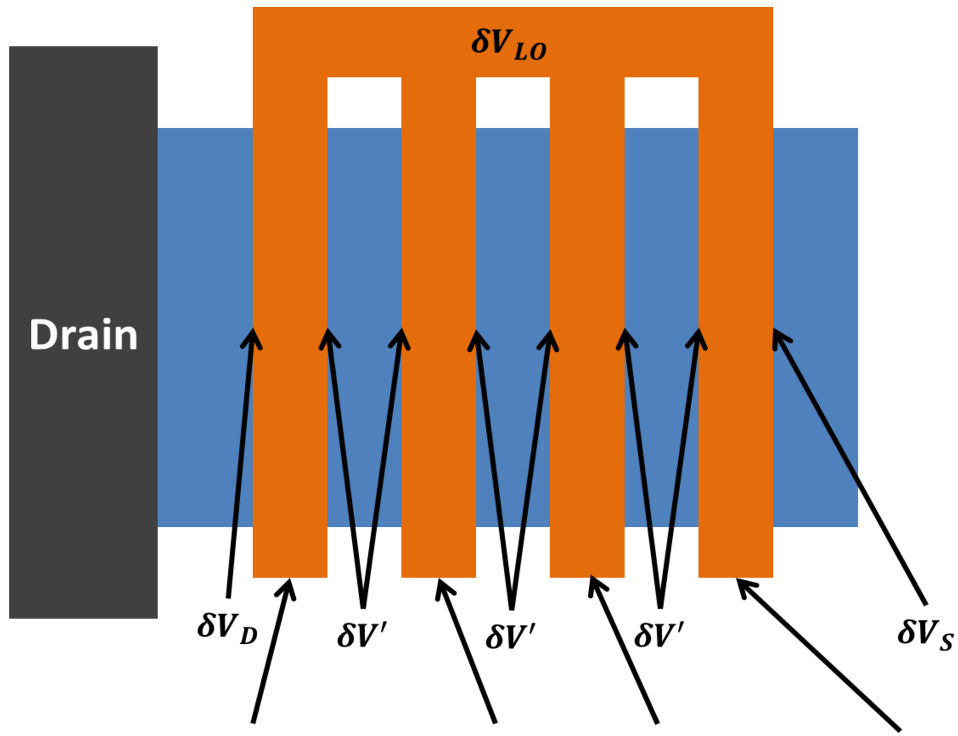
$$q \equiv \beta + i\alpha$$

3 gates, response vs. transport



$$\langle \delta V_{DS} \rangle = -G_{DS} \frac{\partial R_{DS}}{\partial V_{G2}} \langle \delta V_{LO}(t) \, [\delta V_D(t) - \delta V_S(t)] \rangle$$

Four stripe rectifier



$$\langle \delta V_{DS} \rangle \propto \delta V_{LO}[(\delta V_D - \delta V') + (\delta V' - \delta V') + (\delta V' - \delta V') + (\delta V' - \delta V_S)]$$

$$\Rightarrow \langle \delta V_{DS} \rangle \propto \delta V_{LO}[\delta V_D - \delta V_S]$$

Scalability